The TREND IN ENGINEERING

at the University of Washington

7

In this issue:

STACK-SAMPLING EQUIPMENT

POWER-SYSTEM ANALYSIS:
A PROBLEM OF DYNAMICS

A LOW-LAG ALTIMETER FOR AIRCRAFT

ELECTROMAGNETIC FLOWMETER
DESIGN AND PERFORMANCE

ADSORPTION OF BINARY HYDROCARBON
MIXTURES ON ACTIVATED CHARCOAL

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As a departure from its regular policy, *The Trend* invites reader comment on the need for a critical review of engineering education, and will publish such material, subject to space restrictions.

CARNEGIE INSTITUTE OFFERS A SOLUTION

ONE OF THE GREATEST EDUCATIONAL FALLACIES I know is the assumption that the ability to solve problems in the field of physical science implies such ability in social and economic affairs. However this may be, there cannot be much doubt that the engineer's professional place in society has rapidly become a very important one. He has been literally flung into industrial management and other responsibilities where social and economic elements are dominant, and he has had to learn to deal with these new responsibilities while on the job and with no fundamental preparation such as he had had in engineering itself. And his part in such affairs, both professionally and as an educated citizen, must become larger with time. I am not one who says it is the engineer's mission to save the country, but I am one who says that if it is to be saved, he must have a very definite hand in it. And he must therefore have an opportunity while in college to begin his educational preparation for this responsibility.

"Thus, for this side of the engineering curriculum I would recommend for all engineers a four-year program, consuming perhaps a fourth of the total educational time, that would lead to the following outcomes: (1) a clear historical understanding of the parallel growth of science and engineering, on the one hand, and social customs, relations, and institutions, on the other, and of how these have reacted on each other—in other words, a social consciousness and a historical perspective of social evolution; (2) the ability to read purposefully in order to make a critical analysis of a problem involving social and economic elements and to arrive at an intelligent opinion about it; (3) the ability to organize thoughts logically and with purpose; (4) the ability to use the English language and thus to express those thoughts effectively; and (5) a continuing interest in all these matters—in other words, the desire to become educated.

"How can this be accomplished in the limited time? I am clear that it cannot be done by offering electives in the conventional subject-matter courses such as English, economics, history, and the like. Even if the entire curriculum were assigned to such credit-hour units, thus eliminating engineering, I still should not believe the student would acquire the integrated, historical view of social development, the scientific attitude, and the essential ability to analyze complex problems in the field of social relations. At least if one is to judge by the current professional contributions of those who pursued such a program when they were in college and now have public responsibilities in these matters, one is not impressed by the effectiveness of that educational plan. I am sure there must be a different approach, at least in the education of engineers. . . .

"The first feature of the program at Carnegie is that it is unified with respect to purpose, and the central core of that purpose is the cultivation of two abilities. One is the professional style of thought. The other is the ability and the disposition to deal with the whole problem. For instance, an engineer installing a labor-saving device would thus take into account, besides the technical and economic advantages, the impact on both the human and the social situations, dealing with the latter with the same professional skill as with the technical and economic factors. . . .

"The program is further unified by coordination, both horizontal and vertical. By horizontal coordination I mean that all the studies in any one semester, especially in the first two years, are related as to method, subject matter, and terminology; and are timed so that the student acquires from one course useful knowledge and abilities when needed in another. By vertical coordination I mean that the grounds covered in the four-year program are closely related in sequence and that there is continuous, orderly advancement to a higher intellectual level. This vertical coordination is planned according to what we call the Principle of Use, which is that only those subject matters will be included in any semester that will be used in later learning and that cannot be taught more effectively later. . . .

"The second feature of the plan is teaching method. In this plan the teacher becomes a coach, a thinking coach; he guides and disciplines the student's thinking, but the student must do the thinking. . . .

"The third feature is continuing experimental development. A pioneering educational venture such as this requires more than setting the objectives and planning a program. It requires, as well, year-by-year revision in the light of experiment and purpose. We started with an experimental class section in each basic subject; then as experience and improvement have justified it, we have increased the number of such sections. . . .

"And, finally, I come to administrative encouragement. My experience is that a program in professional education of the kind here described requires more than faculty attention. Active, persistent, and wholehearted encouragement by the central administration also is essential."

—*The Development of Professional Education,* by Robert E. Doherty, Carnegie Press, 1950.

THE ENGINEERING EXPERIMENT STATION of the University of Washington was established in December, 1917, to coordinate investigations in progress and to facilitate the development of engineering and industrial research in the University. Its purpose is to aid in the industrial development of the state and nation by scientific research and by furnishing information for the solution of engineering problems.

The scope of the work is three-fold:

(1) to investigate and publish information concerning engineering problems of a more or less general nature that would be helpful in municipal, rural, and industrial affairs;

(2) to undertake extended research and to publish reports on engineering and scientific problems;

(3) to provide opportunities for graduate engineers to conduct research under conditions that will most effectively prepare them for professional service.

For administrative purposes the work of the Station is organized into nine divisions:

1. Aeronautical Engineering
2. Chemical Engineering, Industrial Chemistry
3. Civil Engineering
4. Electrical Engineering
5. Forest Products
6. Geology
7. Mechanical Engineering
8. Mining, Metallurgical, Ceramic Engineering
9. Physics Standards and Tests

The control of the Station is vested in a Station Board consisting of the President of the University, the Dean of the College of Engineering as chairman, the Director of the Station, and members of the faculty, representative of the administrative divisions. The Board determines the character of the investigations to be undertaken and supervises the work.

The Station offers a substantial number of research fellowships to highly qualified graduate students who work under the direct supervision of the faculty of the various divisions. Results of major investigations are published in the form of bulletins and reports. Current research findings from the Station's fellowship projects, as well as accounts of its activities, appear in the quarterly journal, *The Trend in Engineering at the University of Washington*. Reprints of articles by members of the engineering faculty and graduate students published in recognized technical journals are also issued by the Station. Requests for copies of the publications and inquiries for information on engineering and industrial problems should be addressed to the Director, Engineering Experiment Station, University of Washington, Seattle 5.

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CONTENTS

Carnegie Institute Offers a Solution 1

Instrumentation in Industrial Hygiene and Air Pollution Developed at the Environmental Research Laboratory *Ross N. Kusian*
Part II: Stack-Sampling Equipment 5
Part III: Controlled-Atmosphere Chamber 7

Power-System Analysis: A Problem of Dynamics *Laurel J. Lewis* 10

A Low-Lag Altimeter for Aircraft *P. C. Wingrove V. M. Ganzer* 13

Electromagnetic Flowmeter Design and Performance Considerations *James H. Fisher* 18

Adsorption of Binary Hydrocarbon Mixtures on Activated Charcoal: Variation of Molecular Weight of Adsorbate *Fernando Oré, R. W. Moulton* 24

Notes and Comments 30
National Recognition for Mechanical Engineering Professors
Engineers in the News

Northwest Road Builders to Meet 30

Sea-Water Desalting by Refrigeration Approved on Contract 32

FRONT PAGE

ROBERT E. DOHERTY began to develop his ideas of professional education during his career with the General Electric Company, and was profoundly influenced by his association with Charles P. Steinmetz. "Two things had particularly impressed him: the sterility of the ideas which he and other engineering graduates had acquired in their education and in contrast the creative power of the ideas of Steinmetz and of his way of using them in dealing with new and difficult situations." Later, as Dean of Engineering at Yale University, Professor Doherty "extended his conception of professional education to include preparation for good citizenship." During his fourteen years as President of Carnegie Institute of Technology he was able, with the cooperation of the Carnegie faculty, to crystallize this vision into what has become widely known as the "Carnegie Plan."

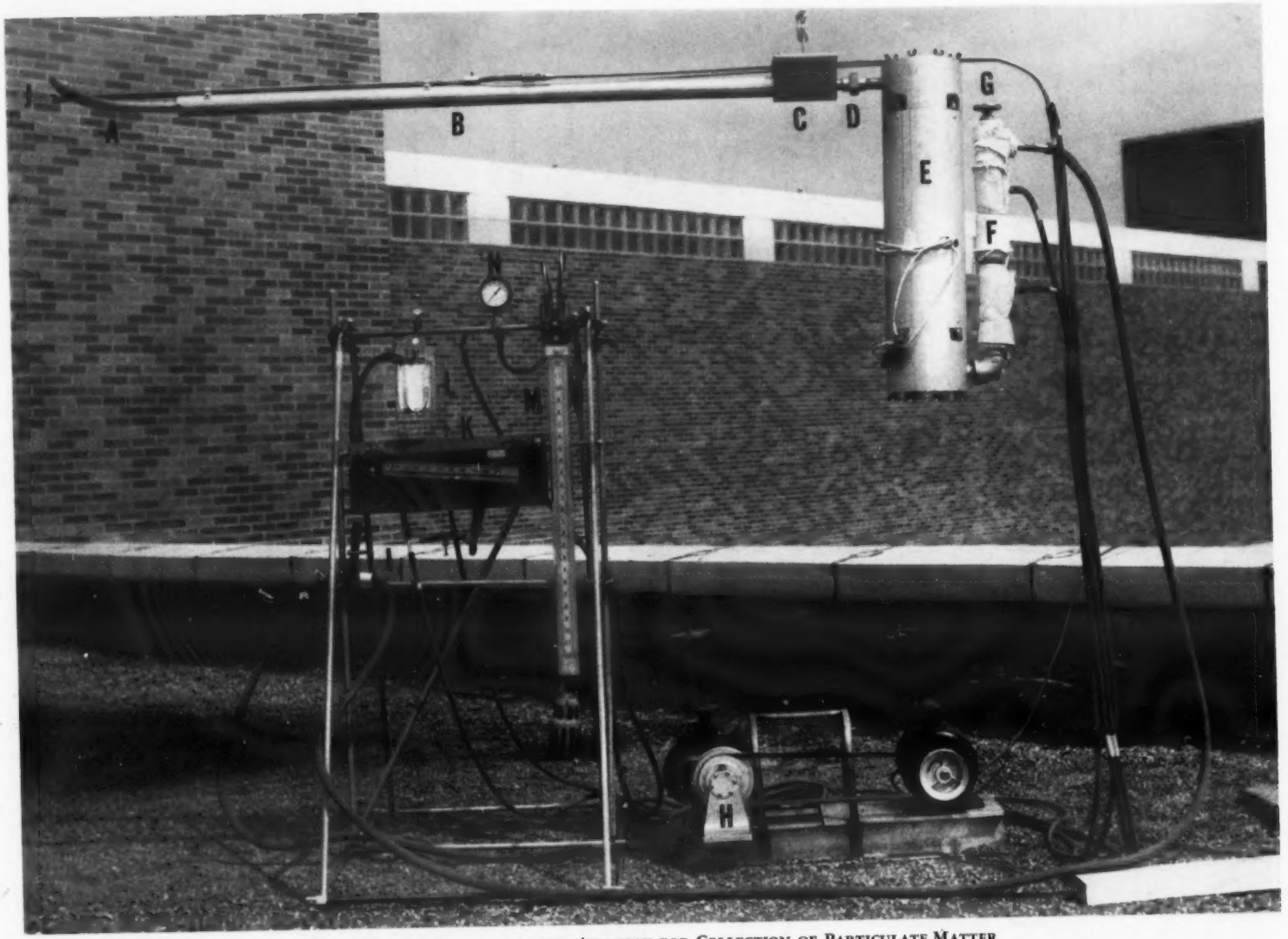

FIG. 1. TYPICAL STACK-SAMPLING ASSEMBLY FOR COLLECTION OF PARTICULATE MATTER

INSTRUMENTATION IN INDUSTRIAL HYGIENE AND AIR POLLUTION DEVELOPED AT THE ENVIRONMENTAL RESEARCH LABORATORY

ROSS N. KUSIAN
Director, Environmental Research Laboratory

Part II: Stack-Sampling Equipment

DATA OBTAINED FROM STACK SAMPLING are valuable not only in determining the extent of pollutant emission but in assisting the designer in selecting control equipment.

Early in the air-pollution survey of Seattle (completed in March, 1952) the need for portable stack-sampling equipment became clearly apparent. A surprising number of industrial representatives were found to have no idea as to what or how much was going up the stacks of their industrial plants.

Unfortunately, neither adequate equipment nor experienced personnel was available in the Seattle area to conduct this type of test. With the ever increasing emphasis on the reduction of air pollution, the staff of the Environmental Research Laboratory decided to develop a stack-sampling unit which would be flexible enough to be adapted to each individual situation. Because no specific funds were allotted for this work, design and acquisition of the equipment has been slow, but, despite the lack of funds, the Laboratory is now in a position to handle virtually any type of stack-sampling problem that may arise in the Northwest.

The original guiding principles in designing the equipment were the following:

1. The testing methods established by the American Society of Mechanical Engineers' "Power Test Codes of 1941: Dust-Separating Apparatus" would be used as a minimum standard.[1]
2. An isokinetic sampling nozzle would be used.
3. Units for collection of the various mists, gases, vapors, and particulate matter were to be included in the design, but were to be planned for interchangeable use.
4. The required stack opening for the sampling device was to be held to a diameter of 2½ in.

Because the ASME Dust-Separating Code is the only generally accepted guide, its testing procedures have been followed closely, except for variations in the calculation methods which allow for better consideration of velocity variations and the effect and amount of moisture in the stack.

Ideally, the velocity through the sampling nozzle should be the same as that of the stack gases being sampled. This isokinetic sampling condition is necessary in order to prevent particulate matter from bouncing off the cushion of slower moving air entering the sampling nozzle, in case the sampling velocity is lower than the stack gas velocity, or to prevent a vacuum-cleaner effect if the nozzle velocities are too high.

In order to maintain constant velocity between the gases in the nozzle and the stack, the "double pitot" or null system was tried at first. This system consists, essentially, of having an orifice for static pressure measurement in the nozzle and another one in the gas stream of the stack. This second pitot tube is mounted on the outside of the sampling nozzle. By varying the sampling rate, the static pressures could be maintained at an equal level, and thus the velocities would be constant. Since large changes in velocities cause only slight changes in static pressure, a differential manometer with a capillary tube using 95 per cent ethyl alcohol and kerosene was connected between the two static pressure orifices.[2] This arrangement gave approximately a 1-in. deflection of the liquid interface for each 0.01 in. of water variation in static pressures.

But although this setup when tested and calibrated in the Laboratory appeared to be an ideal means of maintaining equal velocities, in the field, numerous obstacles arose. The slightest clogging of either of the orifices caused large variations in the manometer and even blowing out of the liquid. In large stacks, a certain amount of liquid condensed in the necessarily long lines, and the resulting liquid traps caused errors in the manometer readings. In addition, the condensate affected the relationship of the specific gravity of the two liquids in the manometer.

The null system of velocity control was therefore abandoned, and, as a compromise, a non-clogging pitot tube* was mounted on the sampling nozzle so

* Manufactured by Western Precipitation Corporation, Los Angeles, California.

that the velocity pressures could be taken near the point of sampling. With this arrangement, the velocities can be corrected about every 30 seconds during a test, by means of a suitable correction chart.

Originally, the sampler was to be designed for use primarily in stacks up to 3 ft in diameter, since the chief need anticipated was for checking smaller installations where little or no collection equipment was in use. On this basis, a short sampling tube and a compact filter-holder were constructed. The sampling tube, pitot tube, and a thermocouple were all mounted in a 2¼-in. OD aluminum tube which easily met the requirements of going through a 2½-in. diameter opening in the stack.

Unfortunately, the first experimental field tests were started on a boiler breeching which was 12 ft wide and 20 ft high, selected because of a long horizontal section where there would be little turbulence. Because of the size, a new nozzle had to be constructed which would reach far enough into the breeching for the recommended traverse. Fuel was hogged wood.

In addition to these manometer difficulties, the long sampling tube, even though shielded, cooled enough to allow condensation before the gases passed through the filter bag. As a result, the moisture produced a large amount of washing effect in the filter. Even though a condenser had been inserted between the filter bag and pump, moisture was carried through it and into the pump, causing erratic flow. Needless to say, the unit was brought back to the Laboratory and completely remodeled.

After a series of modifications over a period of two years, a good workable unit has been developed. Figure 1 shows a typical arrangement for sampling the effluent of a boiler in which hogged wood is burned. In this example, only the particulate matter emission rate was considered.

The stainless steel nozzles* vary in diameter from ⅛ in. to ½ in., and are gradually tapered to the ½-in. stainless steel infiltration tube. The 5-ft filtration tube, shown in Fig. 1-A, is shielded with 1½-in. diameter aluminum tubing (Fig. 1-B). A 6-in. radius is used in the filtration tube (B) since all of the sampling done to date has been on large installations where larger stack openings may be cut if necessary. However, when space limitations occur, a 90° elbow with no throat radius can be used, permitting sampling to be done through a 4-in. diameter hole, in place of the originally specified 2½-in hole. Also, if longer lengths of filtration tubes are needed, additional strip heaters may be installed in order to prevent condensation in the filtration tube itself. The

FIG. 2. MR. KUSIAN ASSEMBLING GLASS BAG FILTER UNIT

unit is suspended from a frame (C) which fastens to the stack or breeching.

At the union (D), special collection equipment, such as disc filter units for nonaqueous mists, miniature cyclones for collecting the larger particles of material, and dust-sizing units, may be inserted for varying types of samples.

The filter-bag holder (E) consists of an inner chamber which is a section of 4-in. diameter aluminum tubing, an outer shell which is a section of 6-in. diameter aluminum tubing, and insulated caps of similar material which are attached by means of thumb screws. Three thermostatically controlled strip heaters are mounted in the insulated space between the tubes, so that the chamber may be maintained above the dew point of the sampled gases. In most cases, a glass filter bag,* 2$^{3}/_{16}$ in. in diameter and 14 in. long is used. The bag is attached to a boss in the chamber with a soft wire clamp (Fig. 2). In special cases, adapters can be used for filter-paper thimbles, etc.

An orifice flowmeter with interchangeable discs is mounted in the vertical section of the 1-in. suction line (Fig. 1-F), and pressure taps lead from the two chambers. A Weston dial-type thermometer (G) is mounted in the tee at the top of the unit. In cases of excessive condensation, this unit may also be lagged and heated by strip heaters.

* Manufactured by Western Precipitation Corporation, Los Angeles, California.

The gas is withdrawn from the stack and through the system by means of a Borg-Warner positive-action rotary blower driven by a ¼-hp electric motor (H). Flow is controlled by a by-pass valve (I). Between the orifice flowmeter and the pump, additional special collecting equipment may be inserted. For example, a series of standard impingers may be used for collection of gases or dusts; freeze-out traps may be used for collection of condensible vapors; and a condenser coupled with a dry-gas meter may sometimes be used to check the orifice flowmeter calculations. (See Fig. 3-a.)

The pitot-tube assembly consists of a non-clogging pitot tube (Fig. 1-J), mounted adjacent to the sampling nozzle and connected by means of copper and rubber tubing to an inclined draft gage (K). The stack static pressures are measured from the static side of this system by means of a small U-tube manometer (L). Stack temperatures may be measured by means of a thermocouple* mounted on the sampling nozzle. In the field, however, it has often been found convenient to use a Weston dial-type thermometer with a 24-in. stem that can be inserted near the sampling point.

The pressure differential in the orifice flowmeter is measured with a 24-in. manometer (M). The exit pressure of the orifice flowmeter is measured with a dial-type vacuum gage (N).

During last summer, this equipment operated quite satisfactorily in sampling a series of stacks which involved chemical and combustion products. With the increased emphasis on reduction of air pollutants, the Laboratory's sampling equipment and service is expected to be in increasing demand by industry.

* Not shown in Figure 1.

Part III: Controlled-Atmosphere Chamber

OCCUPATIONAL ILLNESSES AND DEATHS may be caused by exposure of workmen to high concentrations of an industrial poison. As an example, recently a man entered a solvent tank to clean it, slipped and knocked off his gas mask, inhaled a large quantity of solvent fumes, and died before he could be removed from the tank. Also, occupational illnesses and deaths can be caused by chronic exposures; that is, long exposures to trace amounts of this same solvent vapor (in terms of a few parts of the toxic material per million parts of air) can cause illnesses evidenced by headache, nausea, loss of appetite, and liver damage.

For each new chemical introduced in industrial processes, the question arises: to how large a concentration can the workmen be exposed over a period of years without incurring a chronic occupational illness of some sort? In a nonindustrial application, this very question has recently received widespread public attention in connection with cigarette smoking and lung cancer.

Unfortunately, this question is not answered in many cases until years *after* the illnesses appear. Then, on the basis of incidence rates of the occupational disease being considered and plant studies to determine the environmental exposures of the men, safe limits (threshold limits or maximum allowable concentrations) are set arbitrarily. Of course, this method cannot be considered desirable where the workmen are a part of the experiment.

New products can be tested for chronic toxicity by subjecting small animals with shorter life spans to comparable atmospheric contamination. This can be done by exposing these animals to concentrations equivalent to those which workmen would be expected to encounter. This type of test is conducted in the controlled-atmosphere chamber shown in Figs. 3-b, -c, -d. The animals are not gassed and killed, but are put into the chamber and exposed to trace concentrations of the material under consideration for eight hours, after which they are taken out and put in a normal environment until the next "working" day when they are again exposed. This goes on, five days a week, for a period of weeks or months until the experiment is completed. The animals are then studied by pharmacologists and pathologists who report any traces of disease evident. These data are then interpreted by an industrial physician, who can determine to some extent the effect which the material will have on the workmen.

Figure 4 shows the flow diagram of the controlled-atmosphere chamber constructed by the staff members of the Laboratory.† Supply air, drawn from a fan-room where the temperature remains nearly constant the year around (eliminating the necessity of air conditioning), is forced into the piping system by means of a Spencer midget turbocompressor, powered by a ⅓-hp motor. This unit was used in order to overcome the pressure loss of the air in traveling through the piping, valves, and meters. By regulating the pressure-control valve, a slight negative pressure can be maintained in the chamber itself, a necessary precaution to insure that leaks will drain into the system, and that the test animals will not be subjected to any major changes in pressure.

† Assistance in the original design was given by Dr. Lloyd N. Hazelton, Hazelton Laboratories, Falls Church, Virginia.

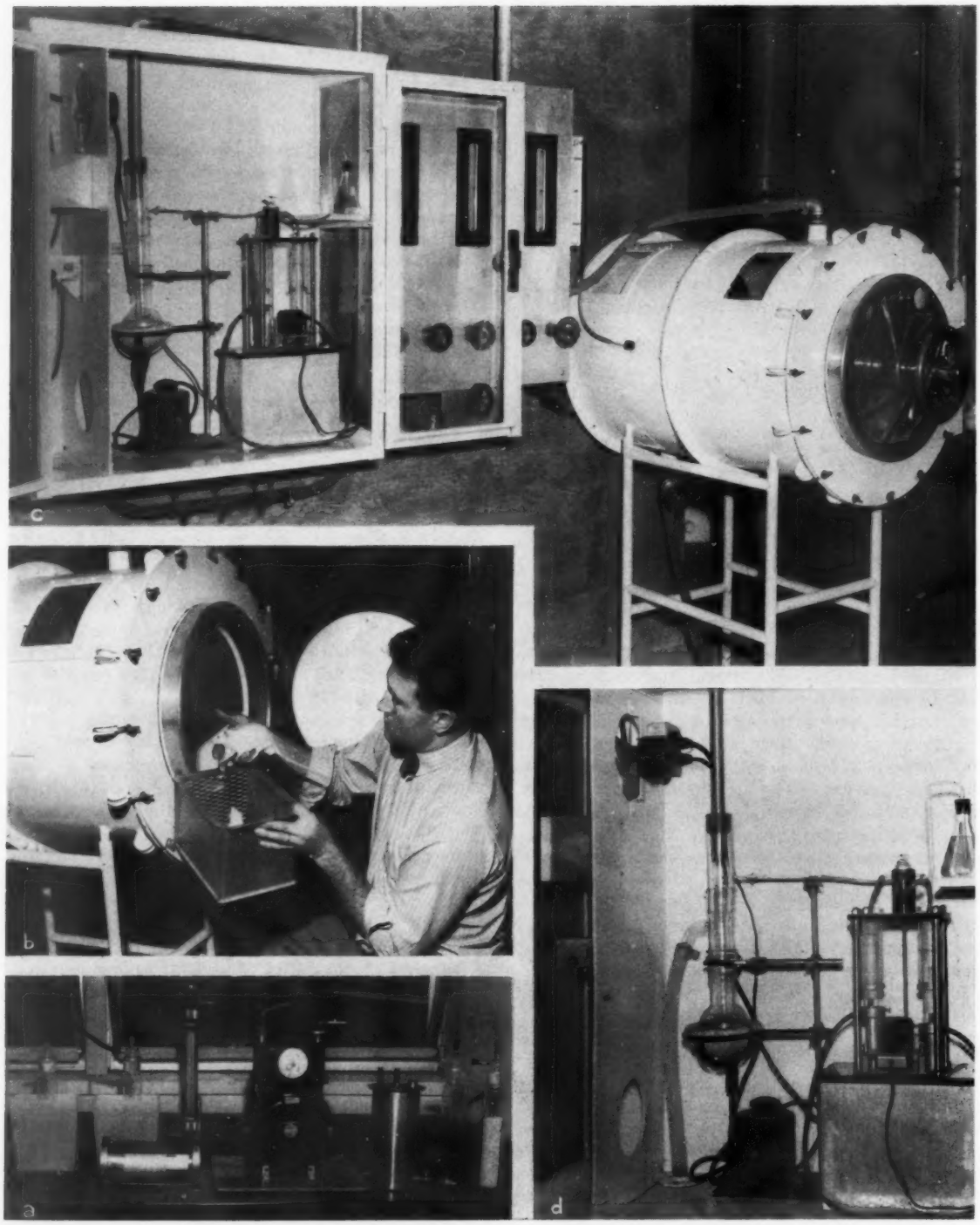

FIGURE 3

a) Some special attachments for stack sampling (*l. to r.*): impingers in ice-bath containers, unit for holding filter-paper thimbles, flowmeter, dry-gas meter, condensing unit, standard impingers; b) Mr. Ransom, pharmacologist, inserting white rat into chamber where it will experience simulated industrial exposure; c) liquid feeder and vaporizer mounted in constant-temperature cabinet; d) general view of controlled-atmosphere chamber.

From the pressure-control valve, the incoming air passes through a Fischer and Porter Flowrator (9.7 to 97 liters per minute) which was built entirely of noncorrosive materials in the anticipation that acid fumes would be one of the test materials.

A Modern Metalcraft automatic liquid feeder, with dual gear-driven syringes, supplies the electrically-heated, thermostatically-controlled liquid vaporizer with a constant supply of the toxic liquid being studied. This portion of the system is mounted in a closed glass cabinet held at a constant temperature by means of an electrical heating element and a circulating fan (Figs. 3-c and 3-d).

Piping to the feeder is ordinary ¾-in. galvanized pipe. Connections from the liquid vaporizer through the chamber are made with 1-in. ID Tygon tubing.

The gas manifold is used to meter gases into the system when a gas or combination of gases is being considered. In addition, dusts may be injected at this point. If necessary, combinations of vapors, dusts, and gases may be run.

From the gas manifold, the mixture flows through a dilution device. Since concentrations as low as one part per million are used, it is necessary to by-pass a portion of the mixture as it comes from the header and add clean air. Valves used for this mixing are brass 1½-in. globe valves. The high concentration discard is metered through another Flowrator (9.7 to 97 liters per minute) and exhausted to the fan.

The 365-liter gassing chamber is constructed of Navy surplus axial fan housing 27½ in. in diameter and 37½ in. long, and is equipped with an autoclave door. Windows are made of plastic. Originally, it was planned to use all stainless steel and glass for both piping and the chamber itself. However, because of the expense involved, brass valves, galvanizing piping (where effect on gas concentration did not matter), and a steel chamber were used. All of these parts were painted with Cotoid, a corrosion-resistant paint. Although extensive tests with corrosive gases have been conducted, virtually no corrosion has occurred.

The quick-opening autoclave door is mounted on a larger hinged door fastened to the end of the chamber shell by swing bolts, and is sealed with a Tygon gasket. The larger door is used for cleaning and removing the hardware-cloth floor mounted 4 in. above the bottom of the chamber. A 1-in. drainpipe connected to a gate valve is used for removal of wastes.

In order to avoid contamination in the laboratory, a fast-purge by-pass valve (1½ in.) is used to speed up the exhausting when the unit is to be shut down.

The total air flow is metered by a Flowrator (55 to 550 liters per minute) before it goes to the exhaust fan in a 1½-in. galvanized pipe. The use of two bleed valves, both 1½-in. globe valves, reduces the noise level. The primary bleed valve is located on the control panel, while the secondary one, used for rough adjustment, is located near the fan.

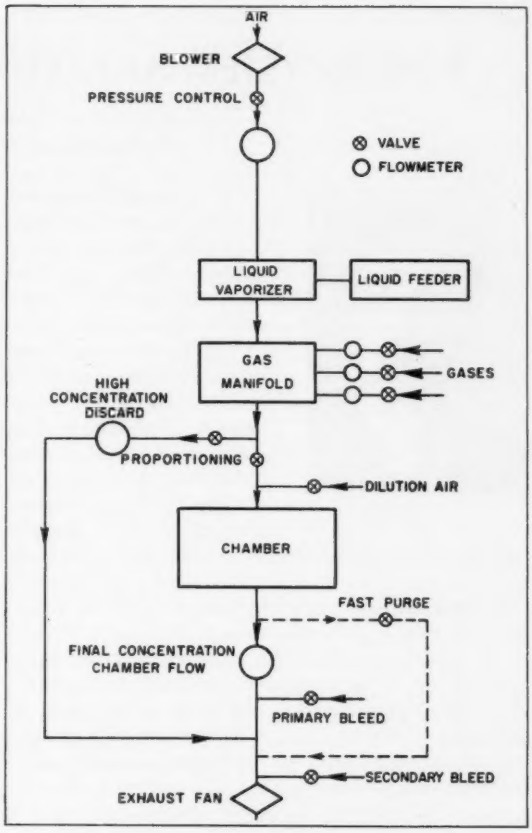

FIG. 4. CHAMBER FLOW DIAGRAM

The exhaust fan is a Tornado Industrial vacuum-cleaner, powered by a 1-hp motor which is mounted on a roof adjacent to the Laboratory.

The system is operated at rates varying from 55 to 350 liters per minute through the chamber, with no build-up of temperature, no pulsation, and very low noise levels in the chamber.

Up to the present time, demand for this equipment has been limited because chronic toxicity studies are lengthy and costly, and, unfortunately, few products are tested in such a manner before they come on the market. However, with more concern being shown over the health effects of air pollution in the form of smog and smaze, a greater interest in the controlled atmosphere chamber is anticipated.

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POWER-SYSTEM ANALYSIS: A PROBLEM OF DYNAMICS

LAUREL J. LEWIS
Professor of Electrical Engineering

L. J. Lewis

The necessity for power development in the Pacific Northwest poses many problems. That additional generation and new transmission lines are needed is quite generally recognized. What is not so widely appreciated is that systems cannot be permitted to "just grow," but additions must be carefully planned in order that the larger systems can perform in a satisfactory manner. The increasing concentration of energy sources constitutes a dynamic system which must be regulated through rigid controls, or else the consequences may become disastrous.

As systems grow, the development of better methods of system analysis presents a continuing challenge. Even though power systems have been developing over many years, it is unwise to assume that all the basic principles are clearly understood or that techniques for analysis are adequate. In fact, methods satisfactory for small systems may lead to unwarranted conclusions if applied to larger systems. This is because analytical methods involve approximations. Factors which may be negligible in simple cases can often be ignored completely; the same factors may have a pronounced effect when the system becomes larger and operating conditions are changed. A continual reappraisal of analytical techniques must therefore be undertaken to assure that methods being employed are adequate to the problems encountered. It is the purpose of this survey to examine the problems requiring analysis, to note the limitations of present techniques, and to consider possible modifications of techniques and alternate procedures which may be required in the not too distant future.

Problems of Analysis

Three problems are of major concern to the system engineer. These are the problems of power flow in a system, the problem of fault protection, and the problem of stability, or the determination of the limit to which the system can be loaded without endangering satisfactory operation. These problems are not new, but must be looked at in the light of growing demands.

Power-flow problems arise, for example, when a new transmission line is planned for connecting two points in a large interconnected system. It is not readily apparent how the power will divide between existing parts of the system and the new portion, or how the power flow will be affected by operating conditions. Such a determination involves the steady-state characteristics of the system, or what is normally encountered at 60 cycles.

It has generally been assumed until recently that this problem was primarily concerned with the electrical characteristics of the system, and that, to obtain the optimum utilization of energy, the system should be designed and operated to minimize the electrical losses consistent with matters of cost. Studies recently made[1,2] emphasize that, for systems depending heavily upon hydroelectric power, a related problem exists involving the control of stream flow, in order to achieve maximum utilization of water resources. In some respects the problem of hydraulic analysis is more complicated than the electrical one. For instance, the amount of power which can be realized from a given stream flow at a power plant is a complicated function of the height of water in the storage reservoir. Water released from one dam on an integrated river development appears as a potential source of energy at a later time at a downstream location, but may or may not be usable depending on the conditions at the lower reservoir and on the load requirements at the time. The management of water resources also involves factors not solely related to power generation. The main objective in power-flow studies is, therefore, not to optimize the operation of the electrical system alone, or the hydraulic system, but to consider the combined problem from an overall point of view. This enlarged concept is so new, and so many variables are involved, that the basic principles are as yet not clearly established.

Fault protection of systems is concerned with system behavior during abnormal conditions. Interrupted service must be restored in a minimum of time and with the least damage to the system. The increasing concentrations of power sources make this problem continually more acute. Not only are circuit breakers of higher interrupting capacities required for the clearing of faults, but the speed of fault clearing must be greatly increased. Circuit breakers have been developed with clearing times less than three cycles and relays which can operate in less than one

cycle. Analytical studies are required to determine the short-circuit currents which might exist at points in the network, as a guide to selection of circuit breakers, and to determine the settings needed for proper relay operations. It is also sometimes important to determine the conditions under which a specific relay should not operate, for those cases where other relays are responsible for clearing the trouble.

To explain the stability problem, a brief description is required of the behavior of a power system under fault conditions. When a disturbance occurs, due to lightning or other causes, normal operation of the system is disrupted. It is the function of the protective equipment, including relays and circuit breakers, to isolate the damaged section in order that normal service may be restored to the balance of the system. However, it may happen that, because of the characteristics of the system involved, restoration of service is possible only under certain conditions. At the generating stations, energy is being fed into the system through large rotating machines; at the various load centers power is being removed, much of it by motors and rotating devices. Under normal operation, a fixed relation exists between the speeds of rotation of various rotating devices, and the system is said to be in synchronism. But when a fault occurs this normal balance is disturbed; machines delivering more power than is being supplied to them slow down, and machines with a fixed input and reduced load speed up. Thus when the trouble is cleared and the machines are again required to operate together, the system is not in a state of equilibrium. If the machines, during the period of disturbance, have been allowed to swing too far apart, then it may not be possible to re-establish synchronism. The system is then said to have exceeded its stability limit. It is a problem of system analysis to determine the maximum power which can be transmitted by a portion of the system for specified fault-clearing times.

The Network Analyzer

Among the analytical tools used for handling power-system problems, the power-system network analyzer has been the most widely used. Many utilities have found it expedient to acquire analyzers to cope with their current problems. An analyzer operates on the analogue principle. It consists of a collection of units which may be connected together, somewhat similar to the way the elements of an actual power system are interconnected; metering equipment is provided to measure voltages, current, and power flow at various points in the system. The analyzer operates at a fixed frequency. To an approximation, it is, in effect, a power system in miniature, operating in the steady state.

The analyzer provides information with moderate effort which could otherwise be obtained only with extensive calculation. However, it has some very definite limitations in its application, as the following discussion will indicate.

A significant portion of system analysis is devoted to power-flow studies. When the effect of adding a new transmission line is sought, since the analyzer is a model of the system, an additional connection can be inserted and measurements made directly to obtain the desired information. The procedure is straightforward, except that, for an extensive system, the analyzer will rarely be large enough to include the entire system. Therefore some portions of the system will have to be considered in a composite grouping for representation. A considerable time may be required to set up the problem.

The analyzer is devised primarily to simulate only the electrical system. Although some attempts have been made to utilize the components of an analyzer in studying related hydraulic problems, the device as a whole is not readily adapted to such use. This is because the significant quantities are not of the same form, and some of the hydraulic parameters are not linear; thus there is no corresponding counterpart in the electrical system.

The problems of relay protection and fault clearing involve transient considerations in which the system performance is not based alone on its 60-cycle behavior. Determination of fault currents often utilizes the method of "symmetrical components," a technique for analyzing systems which are unbalanced. What is often not emphasized is that such a procedure is fundamentally a steady-state process. The results obtained are the values of current which would result if the fault were permitted to persist. No information is obtained as to how the transition takes place. With the increasing emphasis on high-speed fault clearing, the information obtained may have little relation to the critical values of interest.

Analyzers have occasionally been equipped with special switching devices to convert them to "transient analyzers." Faults are then applied and removed in a repetitive manner in order that the voltage changes can be measured and observed on a periodic basis, using oscillographic equipment. The transient analyzer has proved to be a valuable tool. Its principal application is for studying surges and high-speed phenomena which occur in a very short interval compared to the 60-cycle response. However, its use has serious limitations. First of all, the analyzer itself is only a model of the actual system; its behavior is accurate only to the extent that the model is representative. Ordinarily, analyzer units are constructed for representation only of the 60-cycle characteristics. Two systems which may be "equivalent" from the

60-cycle standpoint, may have widely different features, and their transient response may be radically different. Thus the rules usually employed for simplifying systems and combining elements in groups for the steady state do not apply to transient problems. Another limitation of the transient analyzer is that the parameters available for simulating a problem consist of lumped elements, whereas the parameters of a transmission system are "distributed" over the length of a line. Thus, phenomena such as traveling waves which occur on transmission lines cannot be reproduced on a transient basis. The higher the speed of the disturbance being studied, the greater the difficulty in representing it. It often happens that not enough basic information is available concerning the power-system characteristics in these situations, but this is not a criticism of the analyzer.

The determination of the stability limit is of vital importance from an operating standpoint. The conventional analyzer is not capable of making such a determination directly because it is only a limited analogue. Since basically it operates at one frequency only and contains no rotating machines, it cannot include the elements of their dynamic behavior. However, the analyzer can be employed in making such a determination; the process involves what is known as a swing calculation. Such a calculation is an approximate procedure, where it is assumed that the relative angular changes of the machines will take place slowly compared to the time of one cycle of the system frequency. The angular changes are therefore essentially equivalent to changes in relative phases of the machines. The procedure is to set the phases of the machines at the initial phase positions existing at the time of the fault. The power flow is then measured and a determination made of the excess power available to accelerate or retard the rotation of individual machines. From a knowledge of the machine characteristics, one can then calculate how much the machine will accelerate. This acceleration results, a short time later, in a new phase position, establishing a new set of conditions which are then applied to the analyzer, and a second set of power readings obtained. Calculations and measurements are then repeated, step by step, and the sequence of angular changes thereupon converted to a swing curve.

Obtaining a swing curve is a relatively slow and involved process. Particularly with a large system, many hours may be required to complete calculations and measurements for a single set of conditions. A complete study often requires that performance be studied for a large number of cases.

A New Development

In an effort to remove some of the limitations encountered in swing calculations with analyzers, a new development undertaken at the University of Washington is of significance. This project has been directed toward the addition of servomechanisms to a small experimental analyzer which was developed at the University. The analyzer with automatic control is, in effect, a combination analyzer-analogue computer.

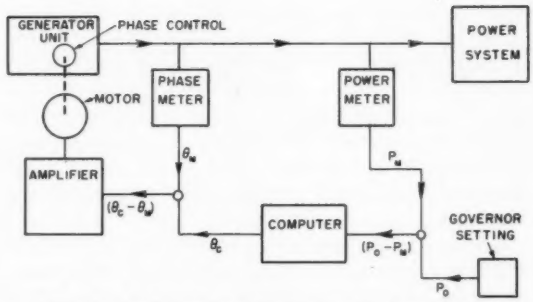

FIG. 1. ANALYZER CONNECTIONS FOR AUTOMATIC CONTROL

The basis of the development may be considered by reference to Fig. 1. The elements illustrated are those associated with only one generator unit; similar arrangements would be provided for other generators here included in the section labeled "power system." Elements include a unit to measure the power supplied by the generator unit to the power system, a unit for measuring the generator output phase angle, a motor for changing the phase angle of the generator unit, and a computing system arranged to control the motor drive in accordance with system requirements.

The system of Fig. 1 will be considered first under normal, or pre-fault conditions. The generator operating at a specified phase position would be delivering a specified power, P_0, to the power system. This would imply a similar power input supplied to the actual machine from the prime mover, controlled by the governor setting. This is an equilibrium condition, and no modification of conditions would be required. For this condition no signal would be applied to the motor to change the phase condition.

Operation will next be examined when a fault occurs in the power system. Immediately a change must occur in the power delivered by the generator unit. The actual power delivered, P_M, as measured by the power meter, is now compared to the governor setting, P_0. The difference provides accelerating power for the actual generator, calling for a change in phase position. The computer unit has the function of calculating the phase angle, θ_c, which is required by the characteristics of the machine. Ordinarily the computed angle, θ_c, will not correspond to the actual angle, θ_M, measured by the phase meter. The error in angle $(\theta_c - \theta_M)$ is therefore applied to the motor to produce a change in phase position so as

(Continued on page 31)

A LOW-LAG ALTIMETER FOR AIRCRAFT*

P. C. WINGROVE
Research Assistant
Engineering Experiment Station

V. M. GANZER
Professor of Aeronautical Engineering

P. C. Wingrove

Almost all aircraft performance continues to be measured through the use of pressure sources located somewhere on the aircraft. A typical example of an instrument for such a purpose is the altimeter, which is nothing more than a pressure gage connected to a pressure source located on the aircraft and reading as close to atmospheric pressure as possible. The altimeter is calibrated according to a standard variation of pressure-with-altitude to read altitude directly. It consists of a case, connected to the static pressure source, in which are mounted pressure aneroids which deflect upon experiencing a pressure change, and thus indicate the pressure altitude. As with most such instruments, the case is connected to the source by a length of tubing which, in some instances, may be quite long. Furthermore, several such devices may be connected to the same tubing so that a relatively large volume of air is available in the instruments.

When pressure changes occur at the source, such as when the airplane is in a dive or climb, some of the air within the instruments must flow through the tubing, and the pressure drop associated with this airflow makes the pressure within the instrument lag behind the true pressure and thus give erroneous readings. In older aircraft, when rates of climb and dive were small, the errors were not great and could be neglected. However, modern aircraft may climb at rates greater than 10,000 fpm, and at such rates the errors in standard instruments may be appreciable.

These errors result in instrument lag. For example, a pilot in a dive might read an altitude of 10,000 ft on his altimeter, while the aircraft is at an altitude 500 ft or more lower than the indicated altitude.

V. M. Ganzer

It should be mentioned that all instruments are not affected in exactly the same way as the altimeter. The airspeed indicator, for example, has two pressure sources, namely total pressure and static pressure, with lines running to each. In this instrument the lag may be in either direction, or zero, depending on relative amounts of lag in the total-pressure and static-pressure systems.

Test-type aircraft usually have large numbers of instruments, and thus large instrument volume, and are particularly liable to have serious lag errors. In test work, where great accuracy is sought, data are corrected for lag to eliminate as much of the error as possible.

This paper deals with a method of revising an altimeter, chosen because of its simplicity, to eliminate much of the error due to lag.

Basis for Design

According to Huston,[1] the performance of a pressure-measuring instrument is similar to that of a one-degree-of-freedom damped oscillator, which mathematically is

$$m\frac{d^2P_i(t)}{dt^2}+B\frac{dP_i(t)}{dt}+\frac{P_i(t)}{C}=\frac{P(t)}{C},$$

when

m = equivalent mass,
B = viscous damping coefficient,
$1/C$ = elastic constant,
$P_i(t)$ = indicated pressure,
$P(t)$ = pressure at the source.

Since in many cases the rate of change of pressure is nearly constant, and since in any case the equivalent

*Condensed and arranged from the thesis of P. C. Wingrove submitted for the degree of M.S. in Aeronautical Engineering, University of Washington, 1954.

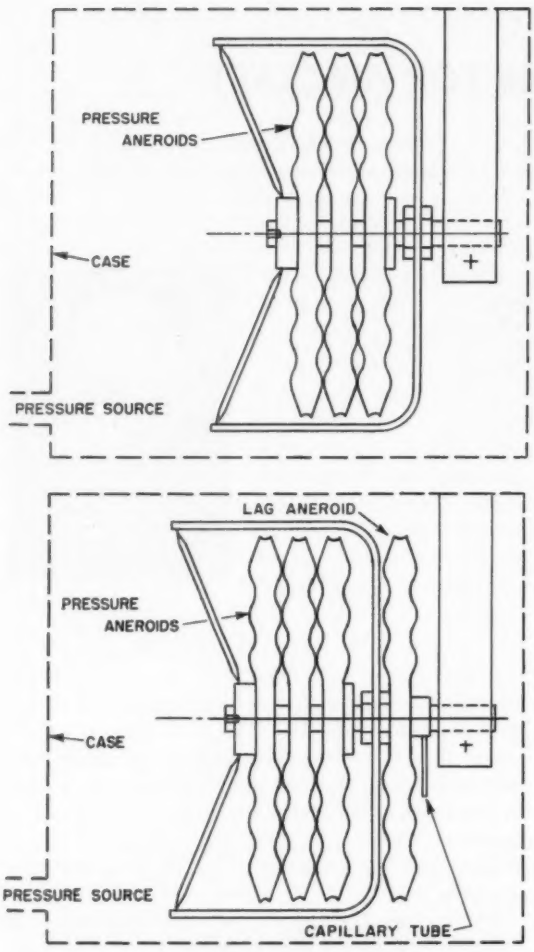

FIG. 1. ALTIMETER DIAGRAMS SHOWING *(above)* STANDARD MECHANISM AND *(below)* LOW-LAG MECHANISM

mass is quite small, the first term may be disregarded and

$$BC\frac{dP_i(t)}{dt}+P_i(t)=P(t)\,. \tag{1}$$

If $\lambda=BC$, where λ is the time lag in seconds,

$$P=P_i+\lambda\frac{dP_i}{dt}\,. \tag{2}$$

This is the equation used by many flight test units to reduce flight test data.

The constant, λ, is determined by the physical airplane system, being proportional to the tubing length and instrument volume and inversely proportional to the inside diameter of the tubing. Moreover,

FIG. 2. LOW-LAG MECHANISM

λ varies with altitude according to the equation,

$$\lambda=\lambda_0\frac{\mu}{\mu_0}\cdot\frac{P_0}{P}\,, \tag{3}$$

where

μ = coefficient of viscosity of air,
P = pressure,
$(\,)_0$ = sea-level condition,

so that

$$P=P_i+\lambda_0\frac{\mu}{\mu_0}\cdot\frac{P_0}{P_i}\cdot\frac{dP_i}{dt}\,. \tag{4}$$

Reference 2 points out that a pressure aneroid vented to a changing pressure through a capillary tube deflects according to the equation,

$$X=-\frac{M\alpha V\mu}{P_i}\cdot\frac{dP_i}{dt}\,, \tag{5}$$

where

X = deflection of aneroid, or dial reading,
M = sensitivity of aneroid,
α = capillary constant $=8l/\pi r^4$,
V = volume of chamber from which air is flowing (the aneroid, in this case),
l = length of capillary tube,
r = radius of capillary tube.

From the similarity of the lag correction term in Eq 4 and the deflection of a pressure aneroid with a

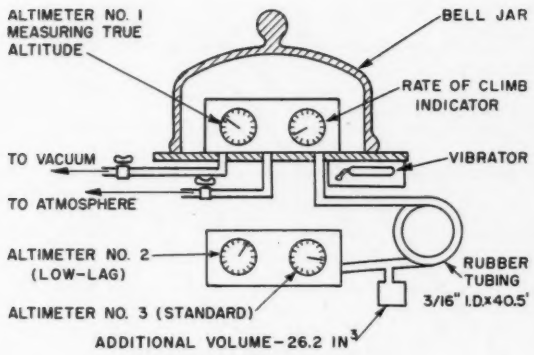

FIG. 3. DIAGRAM OF TEST SETUP

capillary tube as given by Eq 5, it was decided that an instrument could be designed which would use the aneroid-capillary combination to correct for instrument lag. The sea-level lag constant for this system would be $\lambda_0 = M\alpha V\ (\mu_0/P_0)$, which is constant for any given airplane.

Such a lag aneroid was incorporated into the mechanism of a standard Kollsman 50,000-ft sensitive altimeter, as shown in Figs. 1 and 2. As shown, the lag aneroid was placed in the system so that its deflection during pressure changes within the case was added directly to the deflection of the three pressure aneroids in the standard altimeter.

In order to use such an instrument in an airplane, the capillary tube or the instrument volume would have to be adjusted to match the lag constant of the airplane static pressure lines. In the instrument built and tested, a design sea-level lag constant of 0.24 sec was chosen, which corresponds approximately to two altimeters, an airspeed indicator, and a Machmeter connected to a static pressure source with 40 ft of 3/16-in. ID rubber tubing. This resulted in the choice of a capillary tube consisting of a piece of 30-gage hypodermic needle 0.506 in. long, as shown in the photograph in Fig. 2.

The sensitivity of the lag aneroid M, was found by measuring the deflection of the aneroid with capillary tube sealed as pressure was varied, obtaining the deflection per unit change of pressure, and dividing this by the deflection of the three standard aneroids per unit change of pressure.

Test Procedure

A diagrammatic sketch of the test setup is shown in Fig. 3. The air within the bell jar, corresponding to the atmosphere surrounding the airplane, was connected to the standard and low-lag altimeters

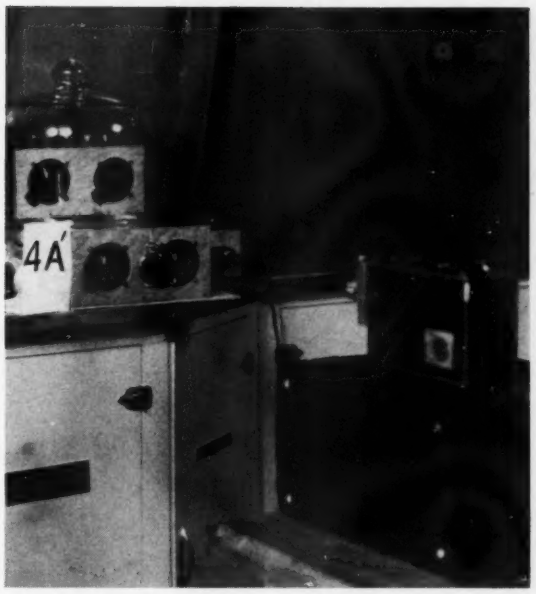

FIG. 4. TEST STAND

through 40 ft of 3/16-in. tubing, and with 26.2 cu in. of additional volume to represent the airspeed indicator and Machmeter. Another sensitive altimeter, placed inside the bell jar, was assumed to record true pressure altitude at all times, even when rates of change of pressure were large.

Climbs and dives were simulated by bleeding air through valves from the bell jar to a vacuum source, or from the atmosphere into the bell jar. Motion pictures were taken of the instruments during simulated climbs and descents. A photograph of the test stand is shown in Fig. 4.

The lag constant of the system was matched to the lag correction given by the low-lag altimeter by varying tubing length until the best agreement was reached. Some of the data obtained, corrected for instrument calibrations, are plotted in Figs. 5 and 6.

The lag constant of the system, determined according to the method of Ref. 1, was found to be 0.212 sec, which is 88 per cent of the value of 0.24 sec, used to design the capillary tube.

Results

Figures 5 and 6 show that the low-lag altimeter followed the true altitude quite closely, although the rates of climb had some effect on the ability of the instrument to indicate true altitude. Since the lag aneroid was incorporated into the design of an existing altimeter, some compromise was necessary, and better agreement under all conditions could

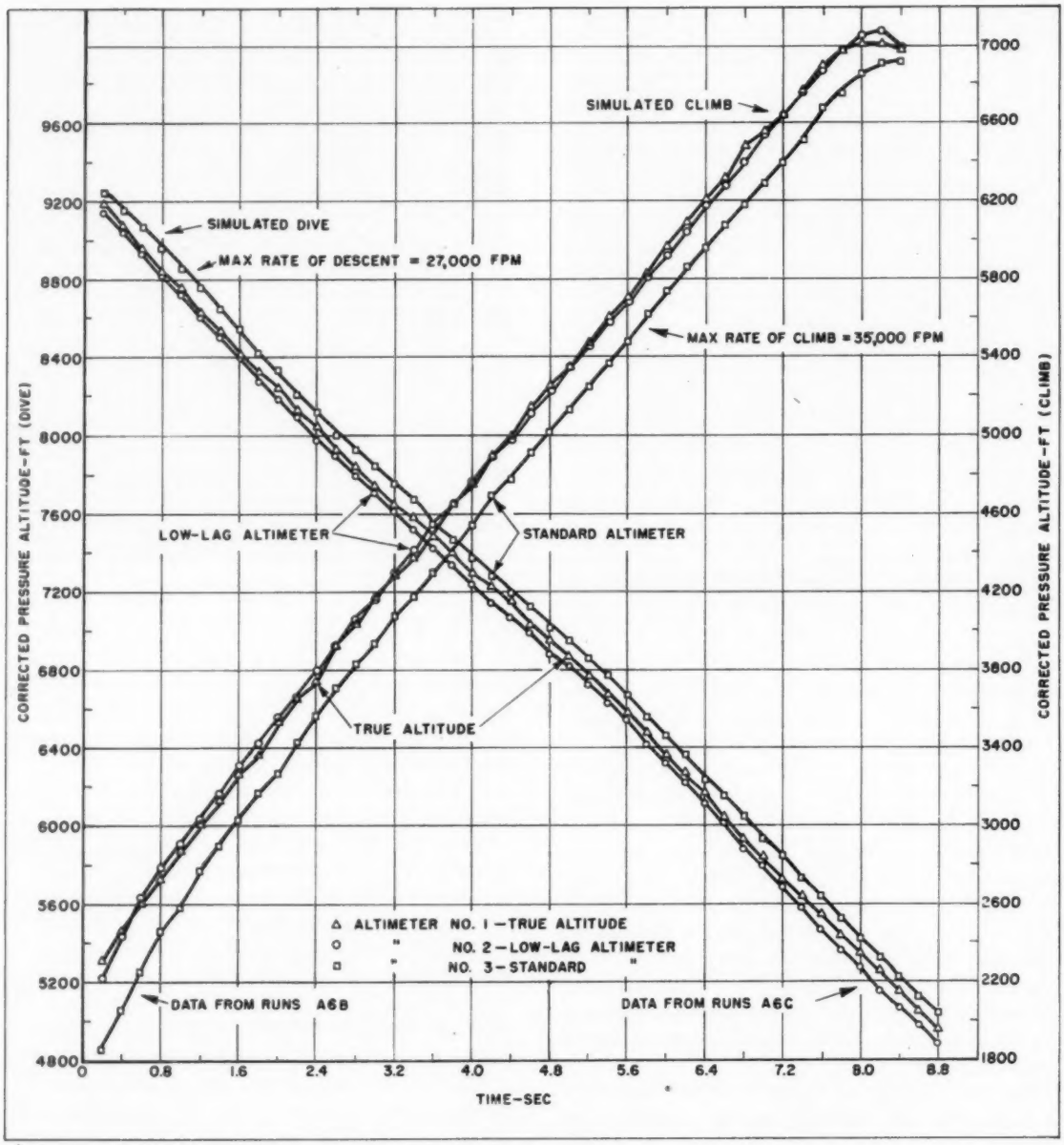

FIG. 5. COMPARISON OF LOW-LAG AND STANDARD ALTIMETER READINGS WITH TRUE ALTITUDE FOR CLIMB AND DIVE AT MAXIMUM RATES OF 35,000 AND 27,000 FPM.

probably be expected from an instrument designed originally to incorporate the low-lag feature.

The method described here for correcting much of the lag of an aircraft altimeter could also be applied to many other aircraft instruments which rely on pressure measurements, such as airspeed indicators and Machmeters.

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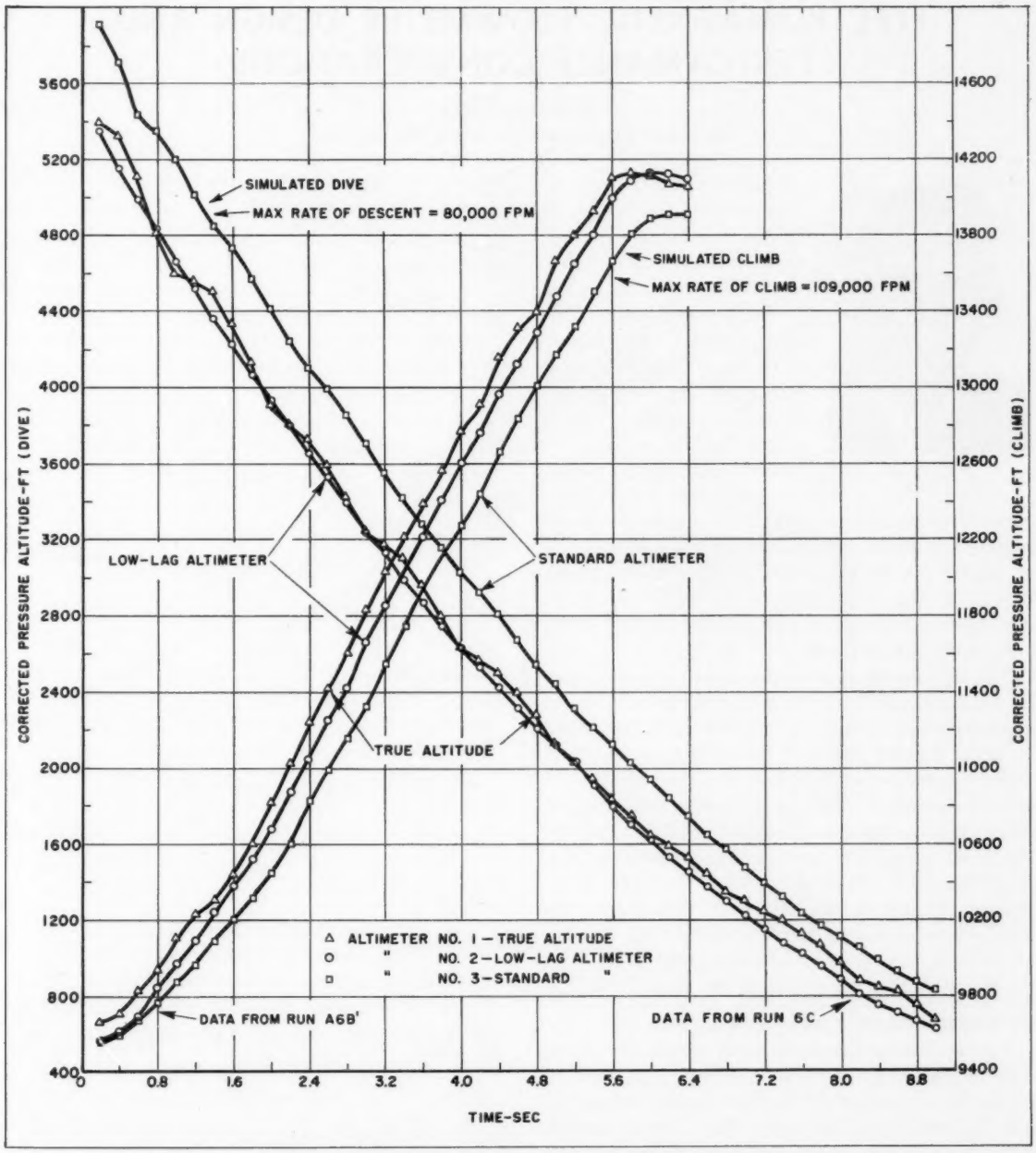

FIG. 6. COMPARISON OF LOW-LAG AND STANDARD ALTIMETER READINGS WITH TRUE ALTITUDE FOR CLIMB AND DIVE AT MAXIMUM RATES OF 109,000 AND 80,000 FPM.

". . . A democratic society can never develop if the individuals composing it are merely specialists with no significant knowledge or beliefs held in common. The only way to organize a society of pure experts who have little or nothing in common with each other is through a dictatorship. On the other hand, the ideal democratic society would see to it that its specialists were liberally-educated men. Liberal education and the democratic ideal are related to each other in a thousand ways. It is not too much to say that they stand and fall together."—GENERAL EDUCATION IN SCHOOLS AND COLLEGES: A Committee Report. Harvard University Press, 1952.

ELECTROMAGNETIC FLOWMETER DESIGN AND PERFORMANCE CONSIDERATIONS

JAMES H. FISHER
Assistant Professor of Electrical Engineering

J. H. Fisher

Accurate measurement of steady-state and transient values of physical variables is of fundamental importance to many branches of science and technology. The precision and performance of the instruments for making such measurements either have contributed to advancing pertinent scientific investigations or still present obstacles to be overcome. Among the most difficult of the measurements required in current research and development work is that of precise determination of dynamic liquid flow rates. One of the most promising devices under development for use in such measurements is the electromagnetic flowmeter.

The electromagnetic flowmeter is an instrument for measuring the instantaneous average velocity of a liquid flowing through a conduit or pipe. Regardless of liquid velocity profile at the cross-section of pipe under consideration, the meter averages the instantaneous velocities across the profile and indicates the instantaneous average. The physical quantity employed to indicate average liquid velocity is the magnitude of a voltage generated in the liquid while flowing through a magnetic field. Theoretical response time of such a meter is limited only by the characteristics of instruments employed to indicate the signal voltage generated by the liquid flow.

Operating Principles and Construction

The transducer portion of the flowmeter is the sensing head, shown in Fig. 1, in which the motion of the liquid passing through a magnetic field gives rise to the signal voltage. The liquid, passing through the flow section comprising parts (1), (2), and (3), moves through the magnetic field set up in the air gap of magnetic structure (4).* The magnetic structure, composed of laminated transformer steel, receives the magnetic field energy from field coils (6) which are connected electrically to an a-c power source. Calibration coils (7) are wound on the magnetic circuit leg containing the flow-section air gap, and produce a voltage indicating the density of the air-gap magnetic field. The signal, generated by the liquid flow, is taken from the sensing head by means of electrodes (8) set diametrically opposed in the walls of the flow section and flush with the inside wall so that contact is made with the moving liquid without flow interference.

To a first degree of approximation, the magnitude of the flow is given by the familiar equation,

$$E_s = (\mathbf{vBL}), \tag{1}$$

where

v is the mean liquid velocity in meters per second,
B is the magnetic flux density in webers per square meter,
L is the distance between electrodes in meters,

Further consideration[1] of the mechanics of flow-signal generation, however, indicates that the signal cannot be independent of electrical properties of the liquid in which it is generated. Thus, a better figure for the flow signal can be obtained with

$$E_s = \frac{\sqrt{\left[\frac{\omega K_0}{\sigma}\right]^2 + \left[1 + \frac{\omega^2 K_0^2 K(K-1)}{\sigma^2}\right]^2}}{1 + \frac{\omega^2 K^2 K_0^2}{\sigma^2}} (\mathbf{vBL}), \tag{2}$$

where

K_0 is the permittivity of free space,
K is the relative permittivity of the liquid,
σ is the unit conductivity of the liquid,
ω is the angular frequency of field alternation,

all expressed in rationalized mks units. Equation 2 is usually abbreviated to the form,

$$E_s = \alpha(\mathbf{vBL}), \tag{3}$$

and α is termed the attenuation factor. Equation 3 is, in reality, the triple scalar product of the vectors **v**, **B**, and **L**, when said vectors are mutually orthogonal, and thus can also be expressed in determinant form utilizing scalar components of the vectors. Theoretical studies[1] have shown the attenuation factor, α, to be negligible in many practical cases, though it should never be ignored as a part of the over-all flowmeter problem.

*The support block (5) is sometimes omitted from the construction.

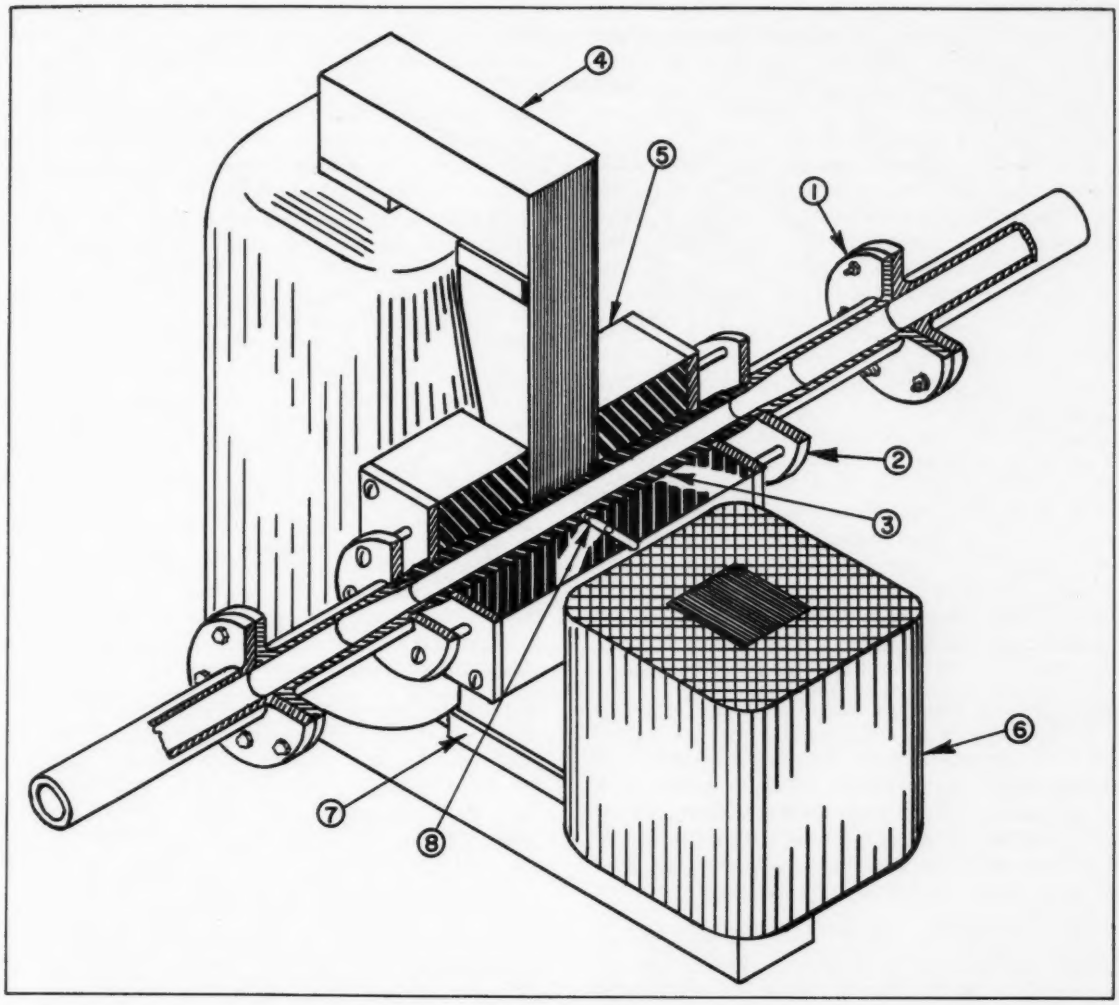

FIG. 1. SENSING-HEAD ASSEMBLY

Figure 2 is a diagrammatic drawing of the complete flowmeter system. The magnetic field power source can be either a battery or generator for flowmeter operation with an invariant field, while an alternating magnetic field can be obtained by energizing the field coils from an oscillator-driven amplifier or an a-c generator. In either case, the impedance of the power source must be matched to that of the field coil circuit in order that sufficient energy may be transferred to the coil circuit to yield the desired magnetic flux density in the air gap.

The cathode follower and balancing unit element of Fig. 2 should be physically located so that the length of the electrode connections (E) are as short as possible, since the purpose of the cathode follower is to match the high impedance at the electrodes of the sensing head to the relatively lower impedance of the amplifier input. The purpose of the balancing unit is to neutralize a voltage which is induced in the liquid by the alternating magnetic field when the liquid is at rest. The neutralization is accomplished by operating on voltage obtained from calibration coils (C) so as to produce a voltage equal in magnitude and opposite in sign to the undesired voltage. The two voltages are then added, resulting in the neutralization. The neutralized voltage is referred to as the transformer voltage, and will be discussed thoroughly in a following section.

The magnitude of the flow signal developed in the sensing head varies over a probable range of 10 microvolts to 10 millivolts and is normally amplified to some larger and more useful value. Amplifiers with

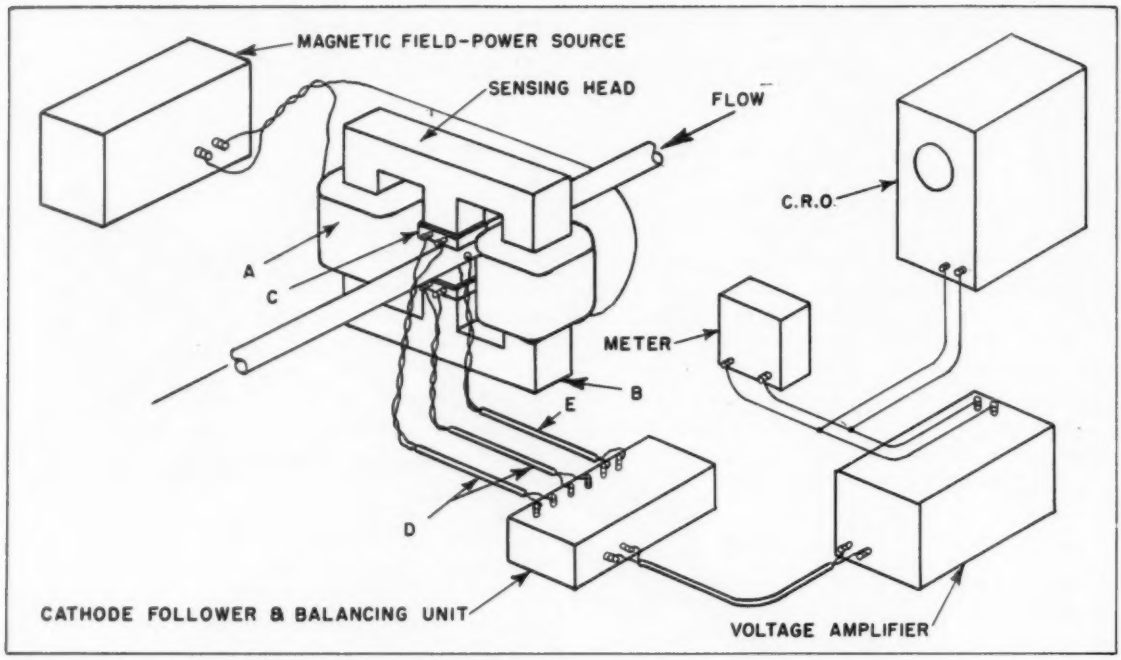

FIG. 2. BLOCK DIAGRAM OF ELECTROMAGNETIC FLOWMETER

gains ranging from less than a thousand to nearly a million have been employed by various investigators[2,3] for the purpose of amplifying such flow signals. Precautions must be taken to reduce noise and pickup to a minimum in these amplifiers, and the most sensitive flowmeters employ selective narrow band-pass amplifier circuits to overcome the noise problem, even though response time of the flowmeter is thus lengthened.

The amplified flow signal is fed from the amplifier to any combination of indicating devices, the one suggested by Fig. 2 being a cathode ray oscilloscope and an ordinary indicating voltmeter. By proper use of a wattmeter,[1] the flow signal can be integrated and the total flow over a given time recorded.

Industrial and Research Value

The unique value of the electromagnetic flowmeter to industry and research, lies in its theoretical combination of properties which are found grouped together in no other flowmeter. The most outstanding properties are (1) lack of moving parts, (2) bilateral response, (3) negligible pressure drop, (4) insensitivity to viscosity, density, temperature, and velocity profile of liquids, (5) applicability to corrosive liquids and liquids containing some solid matter, (6) adequate accuracy at low flow rates, and (7) response times limited primarily by the electrical circuitry.

Several fields of use for a completely developed flowmeter with these characteristics immediately suggest themselves. Item (5) offers promise of applications in the field of chemical engineering, while (2) and (7) may make possible more refined and revealing measurements in the fields of hydraulic controls and jet engine combustion studies where rapidly changing and oscillating flows are frequently the cause of unsatisfactory operation. Finally, properties (3) and (6) are making possible certain biological measurements[4] which could be made in no other known manner, and they also offer hope for the study of flow patterns in streams, rivers, and other bodies of water, which are of interest in several fields of natural science.

In spite of the excellent prospects indicated by these advantages, however, certain considerations prevent the designer from simultaneously realizing the maximum potential of each one of the entire group of properties. Thus, design concessions must be studied to determine the optimum combination for any given application.

Design Considerations

As in most engineering design problems, the flowmeter designer must select the best compromise between some desired standard of flowmeter performance and the complexity of flowmeter construction. In considering performance, the designer must decide on the desired speed of response, the accuracy required, the nature of the liquids to be handled, the ranges of operating pressures and temperatures, and

the capacity of flow to be metered. The more stringent the requirements placed on any one of the above features, the greater will be the complexity of flowmeter construction.

Electromagnetic flowmeter design is further complicated by the necessity of eliminating or suppressing undesirable signals, noises, and other effects originating both inside and outside of the flowmeter. An understanding of these extraneous effects is essential to a solution of the design problem. The flow signal should vary linearly with the magnetic flux density, the velocity of liquid flow, and the distance between the electrodes. Any effect, tending either to alter the magnitude of the flow signal from its theoretical value or to disturb the aforementioned linear relationships, reduces the performance of the flowmeter and must be considered in flowmeter design. The following eight phenomena, though not a part of fundamental operational theory, alter the flow signal to such an extent that, if disregarded in designing, they will seriously reduce flowmeter accuracy and reliability.

1. ***Polarization and contact potential.*** Experiments with electromagnetic flowmeters employing invariant magnetic fields[5] have shown that a large part of the flow signal does not appear at the sensing-head electrodes when the flowmeter is used to measure the flow rate of electrolytes. The loss of signal is due to a polarization potential set up by the electrolyte at the surface of the electrodes in opposition to the signal voltage. Since the flow signal is invariably lower than the critical electrode potential which can be thus formed, the signal loss is present in all d-c flowmeters. The polarization problem has been partly solved in some cases by specially prepared electrodes, such as copper-plated electrodes in the flow-rate measurement of copper sulphate solutions and graphite-coated electrodes for use with water. The use of an alternating magnetic field is always effective in reducing polarization although, as will be seen in a following discussion, 60-cps alternations do not completely eliminate it.

2. ***Attenuation factor.*** Mentioned in a previous section, and defined by Eq 2 and 3, attenuation factor presents a problem with no apparent solution in operating regions defined by liquids with conductivities less than 10^{-7} mho-cm^{-1} in combination with operating frequencies above 10 kc. Other problems, however, place more severe restrictions on current flowmeter construction than does attenuation factor, and the problem of attenuation is commonly evaded by avoiding the operating region where it becomes critical.

3. ***Stray pickup, noise, and coupling.*** Stray pickup and coupling introduce undesirable signals into the sensing-head and amplifier circuits, along with the flow signal. Careful shielding of the high-impedance low-signal level circuit elements, along with general shielding of the entire flowmeter, will reduce pickup and coupling to acceptable levels. In particular, the magnetic field coils, the flow section in the sensing head, and the electrode-to-cathode follower connections should be thoroughly shielded. Reduction of noise can be obtained by the careful selection of magnetic materials, avoidance of any stress in the magnetic core, and low operating potentials in the vacuum tube plate and filament circuits. Battery operation is desirable but not essential; however, best results are obtained with d-c filament operation.

4. ***Circulating currents.*** Circulating currents can arise either from the conductivity of the flow-section walls being of the same order of magnitude as the conductivity of the flowing liquid, or from electrical currents flowing in the liquid as a result of the liquid coming into contact with the ground of a common electrical system, such as the city water pipes. High resistivity of the flow-section walls and a low resistance path from one end of the flow section to the other will solve the problem of circulating currents. Ordinarily, metal pipe or flange connections at each end of the flow section will provide a low resistance path around the flow section when the metal connections are firmly fastened to a heavy metal shielding case, which is normally placed around the entire sensing-head assembly.

5. ***Transformer voltage.*** The liquid in the flow section of the sensing head, the electrodes in the flow-section wall, and the wires connected to the electrodes, when all considered as a single unit, form a loop in the magnetic field of the sensing head. A voltage is induced in this loop in a manner analogous to induction in the windings of a transformer, and the induced voltage is described by

$$E_t = K d\mathbf{B}/dt, \tag{4}$$

where K is a constant determined by the geometry and coupling of the magnetic circuit and the loop. If the flux density, $\mathbf{B}$, is described by the equation

$$\mathbf{B} = \mathbf{B}_m \sin \omega t, \tag{5}$$

then E_t is seen to be directly proportional to the operating frequency, ω, and 90° out of phase with the signal voltage E_s as given by Eq 1. While transformer voltage can be reduced by minimizing the area of the aforementioned loop through which the magnetic flux can pass, it may still be several times as large as the signal voltage. A simple vector addition of E_s and E_t will indicate that small changes in E_s can be entirely masked by E_t, since

the quantity usually indicated by a meter is proportional to the modulus of the vector sum. Hence, suitable operation of the flowmeter can be obtained only by complete neutralization of the transformer voltage in a manner described in the section, "Operating Principles and Construction."

6. ***Microphonics.*** Most systems in which liquid flow is taking place exhibit mechanical vibration at frequencies characteristic of the mechanical system and due to the transmission of energy from the flowing liquid to its surrounding mechanical enclosures. Further transmission of this energy to the elements of the cathode follower and amplifier vacuum tubes will cause forced oscillation of these elements, and lead to spurious signals arising in the tubes. Such microphonic signals will result in erroneous indications of flow rate having little or no correlation with the true flow signal. On an oscilloscope, microphonic signals are ordinarily recognizable by a frequency which is different from the operating frequency and an amplitude which is frequently independent of small changes in fluid flow rate. Microphonics are most effectively removed by proper location and shock-mounting of the electronic equipment. As indicated by the name, microphonics may also arise when acoustic energy available in the vicinity of a vacuum tube reaches a sufficiently high level, and thus acoustic insulation may also be necessary around the electronic apparatus. A typical application where need for acoustic protection would arise is in an engine test cell.

7. ***Harmonics.*** Either saturation of the iron core in the magnetic circuit or nonlinear operation of the amplifier circuits will give rise to harmonic components in the output signal. With reasonable design and care in operation, the amplifier circuits will be found to have a negligible effect on the quality of flowmeter performance. Quite the converse is true of the magnetic circuit saturation. Even though great vigilance is observed in the design and operation of the magnetic circuit, small amounts of odd harmonics will be found in the transformer voltage. Simultaneous neutralization of fundamental and odd harmonics in the transformer voltage is a much more difficult problem than is the neutralization of the fundamental alone. Thus, it is desirable to reduce such harmonics to values small enough to be tolerated rather than to attempt their neutralization. Sufficient care in design of the magnetic circuit and its power source, plus the use of selective filtering, will produce acceptable results.

8. ***Internal impedance of sensing head.*** When flow rates of liquids with conductivities less than 10^{-7} mho-cm^{-1} are measured, the resistance of liquid between the electrodes may be from 10^6 ohms on up to values which make the flowmeter inoperable. The

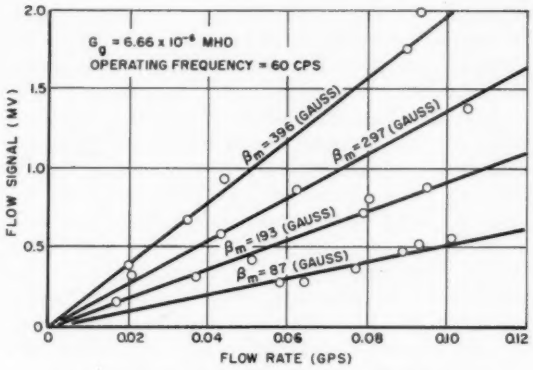

FIG. 3. CORRECTED FLOW SIGNAL VS. FLOW RATE

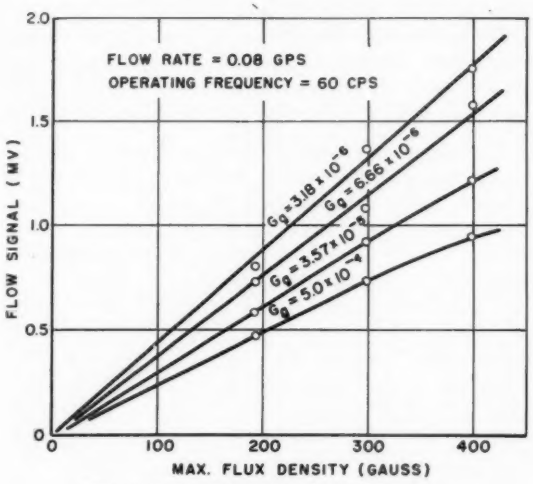

FIG. 4. FLOW SIGNAL VS. FLUX DENSITY

relationship between the flow signal and the interelectrode resistance is analogous to that between the generated voltage of a generator and its internal impedance. Thus, since the true flow signal is analogous to generated voltage, it can be found only by adding the internal resistance drop of the sensing head to the voltage measured at the electrodes. The voltage so obtained is called the corrected flow signal.

Flowmeter Performance

Theoretical performance in an electromagnetic flowmeter requires linear variation in flow signal with variations in flux density and flow rate. Performance of this type is predicated by Eq 1 and 2, provided the characteristics of the flowing liquid are constant. Variations from theoretical performance are most commonly caused by noise and polarization of the electrodes.

The curves of Fig. 3 indicate variation of flow signal as a function of flow rate through a flowmeter in

which the noise has been reduced to an acceptable level. The flowmeter is of the same general type outlined in Figs. 1 and 2, and the parameter on each curve is a constant maximum flux density, as indicated. The interelectrode conductance, G_e, is 6.66 x 10^{-6} mho for all four curves, and the frequency of operation is 60 cps. Figure 3 comprises one set of a group of curves where the variable from set to set is the interelectrode conductance. Variations in interelectrode conductance were obtained by varying the acidity of a water-nitric acid mixture. A random variation of flowmeter readings, about the mean of the curves, limits the accuracy to approximately five per cent of full scale, although greater accuracy can be obtained at the expense of additional cost and care in design and construction. Figure 3 demonstrates flowmeter linearity both as a function of flow rate and flux density; however, linearity with flux density is pointed out more clearly when cross plots are made with flow constant and flux as a variable.

Figure 4 shows a set of curves obtained by cross-plotting several sets, such as the one shown in Fig. 3. The parameter of the curves in Fig. 4 is interelectrode conductance which has been varied by altering the acidity of the flowing test liquid, as mentioned above. The flow signals as plotted in Fig. 4, have already been corrected for internal resistance drop in the sensing head. Thus, the decrease in flow signal with increasing interelectrode conductance must be attributed primarily to polarization at the electrodes. Although much of the flow signal is lost as a result of polarization, Fig. 4 indicates that the flowmeter retains a linear relationship between flux density and flow signal so long as the interelectrode conductance is constant. Additional investigation has shown that the flowmeter also retains linearity between flow rate and flow signal with constant interelectrode conductance.

Figure 5 presents a more complete picture of flowmeter performance as a function of test liquid acidity than is given by Figs. 3 and 4. Four curves of flow signal vs. interelectrode conductance are plotted to a logarithmic scale in Fig. 5. The curves are all for the same constant flow rate and constant flux density. Curve A is for theoretical performance to be expected from a flowmeter with an infinite amplifier input impedance and with an attenuation factor of unity; thus, this curve represents the best possible performance. Curve B is the theoretical performance to be expected from a flowmeter with an amplifier input impedance of 470,000 ohms (the input impedance of the amplifier employed in these tests) and with an attenuation factor of unity. In effect, the difference between curves A and B is the correction for internal impedance drop due to the current drawn from the sensing head by the amplifier. Curve C is the corrected performance curve obtained from experimental data and would coincide with A if the flowmeter performance were perfect over the entire range of test liquid acidity. Curve C coincides with A for tests employing singly distilled water, showing that theoretical performance can be obtained from the electromagnetic

(Continued on page 29)

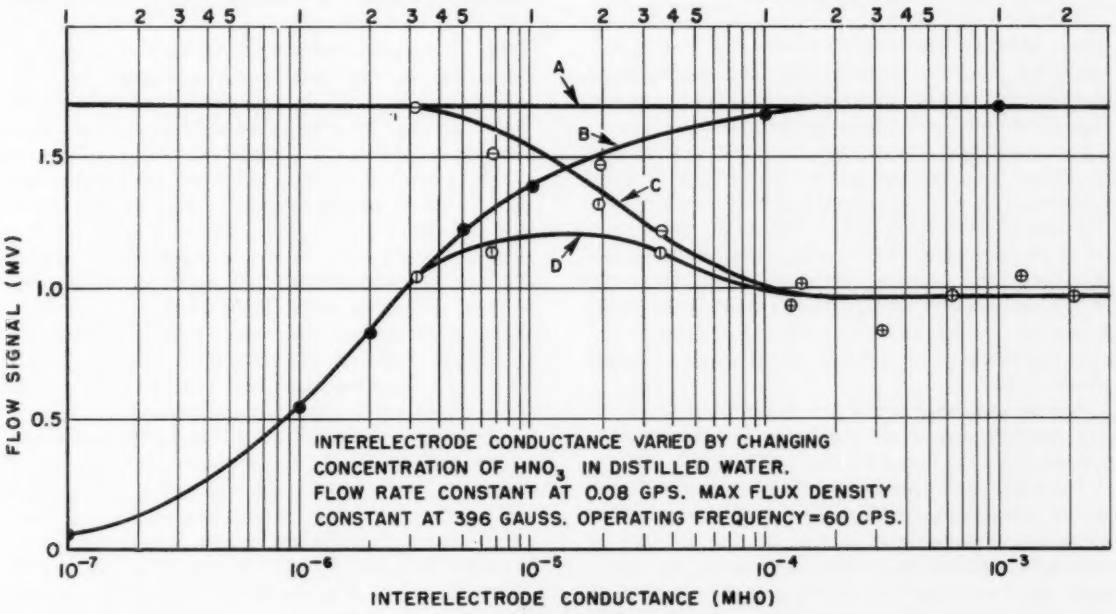

FIG. 5. FLOW CURVES

ADSORPTION OF BINARY HYDROCARBON MIXTURES ON ACTIVATED CHARCOAL

Variation of Molecular Weight of Adsorbate

FERNANDO ORE
Research Assistant
Engineering Experiment Station

R. W. MOULTON
Professor of Chemical Engineering

Fernando Ore

The increasing number of industrial applications of charcoal-based separation systems, especially in the petroleum industry, have given a new interest to the study of the unit operation of adsorption.

The uptake of gases by charcoal has been known for almost two centuries, and during this time important research of this phenomenon has been accomplished; nevertheless, the data so far published fall short of those required for the multiple component systems in which adsorption is involved. Besides, limitations are placed on the usefulness of these data for the design of commercial charcoal-based separation systems because, in large part, they have been obtained under conditions not practical from a commercial standpoint.

Although most of the technical applications or processes involve gas mixtures rather than pure gases, published data deal mostly with simple adsorption, and those available for mixed adsorption have been recorded almost exclusively in dynamic systems.

Gas purification, recovery of solvents, separation of olefins from cracked gases, recovery of liquefied petroleum gases from natural refinery streams, are a few examples of the application of mixed adsorption. Some of these separations with a charcoal-based system have the advantage that low temperatures and high pressures are not required as they would be if a fractional distillation process were used.

It is customary to consider three types of mixed adsorption:

1. Single adsorbent and a mixture of gases.
2. One adsorbate and a mixture of adsorbents.
3. A mixed adsorbent and a mixture of gases.

The first type of mixed adsorption is by far the one of the greatest practical interest, and obtaining data on this type of adsorption was the goal of this research. A study of the molecular weight of the adsorbate, and the factors that influence it, has been made for a static system when binary mixtures of the gases ethane, propane, butane, and ethylene are adsorbed on charcoal.

R. W. Moulton

Apparatus

A detailed diagram of the apparatus is shown in Fig. 1. It consisted of an adsorption bulb (A) connected to a closed-end manometer (B) and to a gas burette (C), all three inside an air thermostat case. Outside of the thermostat the system included a Cenco Hyvac vacuum pump powered by an Emerson electric motor, a modified McLeod gage, and gas manifold lines.

The heating system of the air thermostat case included a 500-watt heating element that could be regulated by a variac, a 50-watt heating element used in conjunction with a Cenco-De Khotinsky bimetallic regulator, and a water-cooling coil of copper tubing. All three elements were installed in front of a four-blade 6-in. fan, rotating at 1,000 rpm. The temperature could be controlled within a range of 0.1° C by adjusting the variac to a position depending on the room temperature, and by keeping a constant flow of cooling water.

The adsorption bulb housed a copper-beryllium alloy spring or sorption balance (e) suspended from the top of the adsorption bulb on a small wire clip fitting in milled grooves on either side of the top brass fitting. Its lower end was connected through a silica fiber (f) to an aluminum bucket (g) which contained the adsorbent. Columbia activated charcoal grade SX, in pellets of 6-8 mesh, was used as the adsorbent in this case. Pin-point holes were made in the aluminum bucket to allow the gas to pass through.

The closed-end manometer was made up of 10-mm pyrex tubing with the closed end 86 cm long. The gas burette consisted of 15 x 20-mm pyrex tubing 67 cm in length, with a 5-cm bulb close to the upper end. The lower end of the gas burette was connected to a leveling bulb (h) by a ¼-in. tygon tubing, forming the leveling line (i). The leveling bulb was suspended from the ceiling by a pulley alongside of an exactly

calibrated meter scale. This leveling line controlled the pressure and volume in the gas burette.

The manifold consisted of $\frac{3}{16}$-in. copper tubing, three $\frac{1}{4}$-in. Hoke stainless steel needle valves (D, E, F), and silver-soldered joints.

Additional parts of the equipment were a manifold tapper installed behind the closed-end manometer to eliminate the lag in the readings, an outgas furnace to outgas the charcoal, an electromagnet, which facilitated reading by reducing the spring oscillations, and a stationary cathetometer to measure the spring elongation.

The spring was calibrated by determining with the cathetometer the spring elongation caused by fractional analytical weights deposited in the aluminum bucket, while keeping the thermostat at a constant temperature of 25° C. The volume of the gas burette was determined from the weight of mercury to fill it. To determine the volume of the adsorption bulb, a certain amount of helium was introduced into the gas burette, and the temperature and pressure were recorded. Then the same helium was allowed to occupy the adsorption bulb and the gas burette, and the pressure and temperature were recorded again. From the known volume of the gas burette, and by applying simultaneous solutions of two van der Waals equations for the two sets of readings recorded, the volume of the adsorption bulb was determined.

Experimental Procedure

The major steps involved in making a binary run consisted of mixing the gases, outgassing the charcoal, and obtaining data for the rate of adsorption and equilibrium.

After exhaustion of the gas burette and manifold with the vacuum pump, one of the gases was put into the gas burette to a pressure which was roughly estimated to give the desired amount of this gas. After the gas was allowed to remain at a constant temperature of 25° C for some hours, a pressure reading was taken by positioning the mercury level in the burette at a reference dot and reading on the wall scale the mercury level in the leveling line. Following another exhaustion of the manifold the second gas was allowed into the gas burette until a pressure which was previously estimated to give the desired composition was approached. Mixing was facilitated by raising and lowering the leveling line several times; then the mixture was allowed to remain for several hours at a constant temperature before reading the total pressure.

The charcoal already in the aluminum bucket was outgassed by using an outgas furnace, which raised the temperature up to 350° C, while vacuum was being pulled continuously on the adsorption bulb.

After the outgassing of the charcoal, the system was thermostated at 25° C for several hours. At the end of this period the pressure in the gas burette was

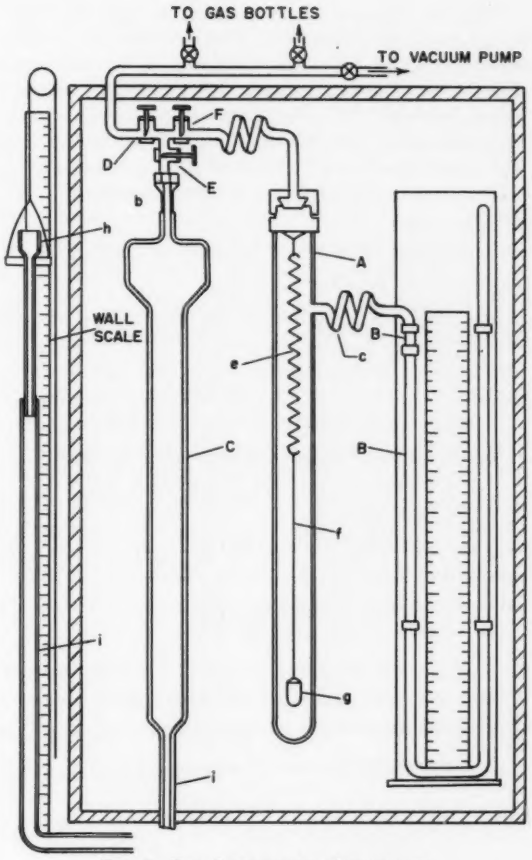

FIG. 1. GAS ADSORPTION APPARATUS

checked again, the top and bottom of the spring were recorded by means of the cathetometer, the manifold lines and adsorption bulb were completely evacuated, and all valves were closed. Just prior to time zero, valve F was opened. At time zero the adsorption bulb valve (E) was opened, allowing the gas into the adsorption bulb, while the oscillation dampener was turned on. The desired amount of gas allowed in the adsorption bulb was approximately estimated by a pressure reading of the closed-end manometer.

Simultaneous readings of the spring elongation with the cathetometer, and pressure readings of the closed-end manometer, were recorded at different times at the nearest second by reference to a stop clock. The runs were continued overnight for periods of 15 to 20 hours, until constant readings showed that equilibrium had been reached.

The pressure of the remaining gas in the burette and tubing between valves D, E, and F was determined by positioning the leveling line with the mercury at the reference dot in the gas burette and then reading the wall scale.

Four binary mixtures were made by different combinations of the gases used. For each binary mixture six runs were made; three runs were carried on at a pressure of approximately 0.7 to 0.8 atmospheres for mixtures in which the heavier component was in the proportion of 0.25, 0.50, and 0.75 mole fraction. The other three runs with the same mixtures were done at a pressure of 0.3 to 0.4 atmospheres.

Calculations

Calculations were made for each instant at which readings were taken.

To determine the volume occupied by a pure gas mole, the van der Waals equation was used:

$$[P+(a/V^2)]\ [V-b]=RT, \qquad (1)$$

where

P = absolute pressure,
a, b = van der Waals constants for pure gases,
V = volume of pure gas per mole,
R = gas constant,
T = absolute temperature.

Solving for V yields

$$V=\frac{RT}{P+(a/V^2)}+b\,. \qquad (2)$$

For calculation involving mixtures $(\ )_m$, the van der Waals equation, with its constants properly corrected, was used:

$$V_m=\frac{RT}{P+(a_m/V^2)}+b_m\,, \qquad (3)$$

where

$$a_m^{\frac{1}{2}}=x_1a_1^{\frac{1}{2}}+x_2a_2^{\frac{1}{2}}\,, \qquad (4)$$

and

$$b_m=x_1b_1+x_2b_2\,, \qquad (5)$$

$x_{(\ )}$ being the mole fraction of a particular component.

The three main steps in the calculations were as follows:

1. ***Calculation of the Number of Moles of Gas Adsorbed***

a) The number of moles of the first gas introduced into the gas burette was calculated from the known volume of the gas burette and V. The value of V was calculated by trial and error, using Eq 2 in conjunction with the pressure and temperature readings. (The temperature was constant at 25° throughout.)

b) The total number of moles of mixture was calculated from the known volume of the gas burette and the value of V_m, which had been previously calculated by using Eq 3 and the pressure and temperature readings. It was necessary first to assume a total number of moles of mixture, then to determine the corresponding gas composition for such an assumed value, and calculate the constants a_m and b_m with Eq 4 and 5, to be used in Eq 3. The volume of the total number of moles of mixture was then calculated and compared with the value first assumed. This procedure was repeated until the assumed and calculated values were the same.

c) The number of moles of gas remaining in the burette was determined by calculating V_m with Eq 3, using the corresponding temperature and pressure readings. From the known volume occupied by the gas and V_m, the number of moles was calculated.

d) The number of moles of gas transferred to the adsorption bulb was calculated by subtracting the number of moles remaining in the burette from the original number of moles of gas.

e) The number of unadsorbed moles of gas remaining in the adsorption bulb was calculated from the known volume of the adsorption bulb and the corresponding pressure and temperature. Equation 3 was used in these calculations, with its constants continuously corrected for the variation in mixture composition due to the different adsorption capacity of the charcoal for each component.

f) The number of moles of gas adsorbed was determined by subtracting the unadsorbed moles from the total number of moles transferred into the adsorption bulb.

2. ***Determination of the Weight of the Adsorbate***

The weight of gas adsorbed for each instant at which readings were taken was calculated from the spring elongation measured by the cathetometer and the spring calibration curve.

3. ***Calculations of the Molecular Weight of the Adsorbate***

The molecular weight of the adsorbate was calculated from the number of moles of gas adsorbed and the weight of the gas adsorbed.

Discussion

The research accomplished made it apparent that the molecular weight, proportion, and molecular structure of the mixture components, in addition to the average molecular weight, boiling point of the mixture, and operating pressure, all influence the molecular weight of the adsorbed gas on charcoal at isothermic conditions. From the data recorded, curves showing the variation with time of the molecular weight of the adsorbate were prepared for the four systems: ethylene-propane, ethylene-butane, propane-butane, and ethane-propane.

Molecular Weight of Adsorbed Mixture: Figure 2 presents, as an example, the corresponding curves for the system ethylene-propane, in which the molecular weight of the adsorbate has been plotted against adsorption time. The molecular weight of the adsorbate appears to be always larger than the molecular weight of the unadsorbed mixture. An increase of the molecular weight of the adsorbed mixture becomes appreciable after time zero. This trend starts

from the initial molecular weight of gas mixture, at which the molecular weight of adsorbate was extrapolated to time zero, and continues to increase until equilibrium is reached.

A study of Fig. 2, and of curves corresponding to the other three systems which are not shown here, reveals that each curve has two different slopes connected by an intermediate section that passes smoothly from the first slope to the second slope, as with most of the adsorption-rate curves reported in the literature. This could mean that the controlling factor in the adsorption during the first part of the run is different from that controlling adsorption in the second part. While the free absorbent surface should influence the first part of the run, it seems reasonable to assume that, on the second part of the curve, the further increase in the molecular weight, after the adsorbing surface has been saturated, is caused by replacement of the lighter molecules by the heavier.

Using the number of moles of gas adsorbed, and the weight of gas adsorbed, the writers calculated the number of moles of each gas adsorbed at each particular time. It was found that the number of gas moles adsorbed of both gases increases with time, until probable saturation of the adsorbent surface; after that, a desorption of the lighter gas takes place, while the heavier gas is slowly adsorbed by the charcoal, till equilibrium is reached. These two periods of adsorption correspond to the two different slopes of the curves. It is possible that the replacement of lighter molecules by heavier ones takes place also in the first period, but the rate at which the light gas is adsorbed on the free adsorbent surface surpassed the rate of displacement; therefore adsorption of light gas continued to take place as long as there was free adsorbent surface. Holmes[1] also reported this phenomenon of desorption of the lighter gas after a certain time. However, the length of time apparently depends on the rate of adsorption, nature of the gases, and amount of adsorbent.

If the increase of the molecular weight of the adsorbate in the second part of the run occurred by replacement, it would seem possible to find a simple relation between the heavier molecules adsorbed and the lighter ones desorbed. However, earlier researchers have reported that the adsorbing surface of charcoal is not the same for all gases. Because of this fact, together with the difference in affinity and molecular

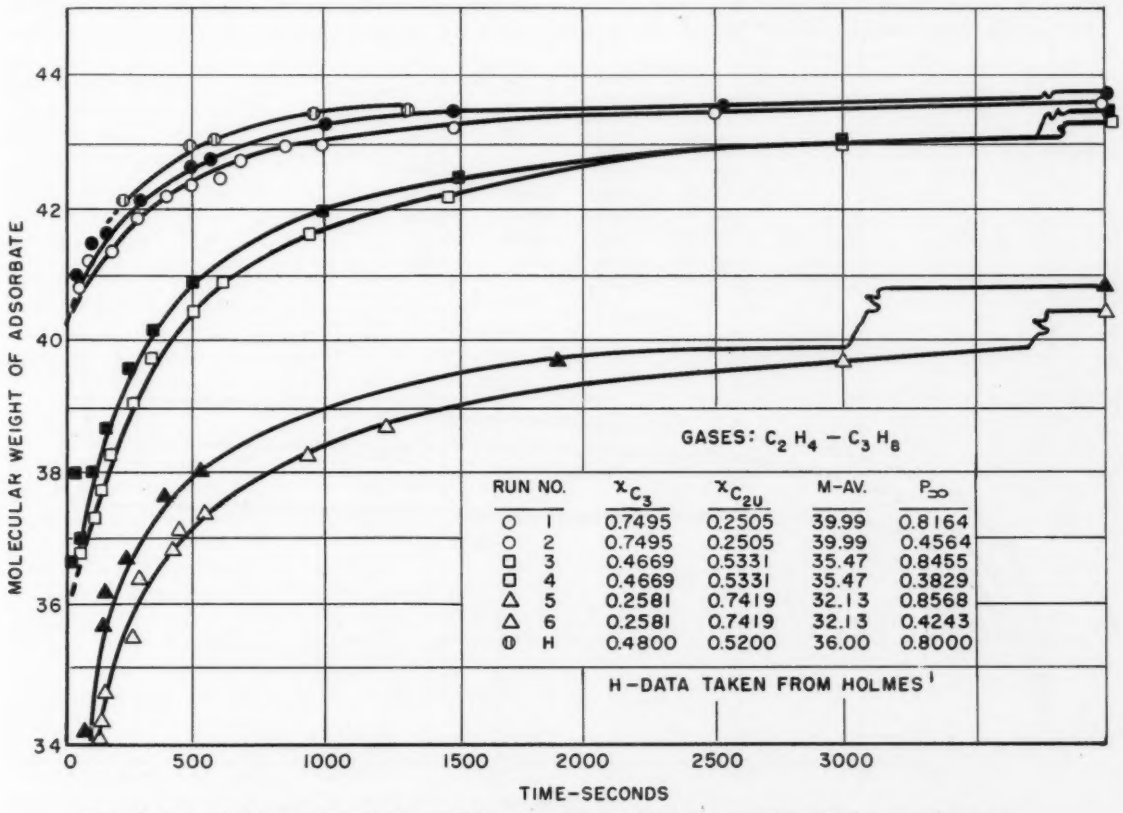

FIG. 2. Rate of change of molecular weight of adsorbate: effect of composition of mixture and pressure.

structure, and the size of the molecules, the relation between the adsorbed and desorbed molecules varies in different mixtures.

Influence of Mixture Composition: The curves of Fig. 2 (and those of the other systems investigated) permit also a comparison of the adsorption curves of the same systems when their components are in different proportions. The molecular weight of the adsorbate approaches the molecular weight of the heavier component as equilibrium is approached; this approach naturally is better for mixtures with a higher proportion of the heavier component, and equilibrium is reached faster when mixtures of a higher percentage of heavier component are used. This difference in the time taken to reach equilibrium is due to a prolonged replacement time when mixtures with lower percentages of the heavier component are used; but for both cases, the time of the adsorbing section of the run is about the same.

The difference in the length of time to reach equilibrium can be explained on the same basis as replacement of molecules. It will take a longer time to have the same number of strikes of heavy molecules on the charcoal surface when mixtures with lower concentrations of heavy components are used.

For mixtures that have different percentages of the heavier component, the difference in the molecular weight of their adsorbates decreases as equilibrium is approached, as may be seen in Fig. 2. These curves indicate that, despite the large difference in initial mixture composition, the adsorbed gas at equilibrium has a high molecular weight in all cases, with values a little different in each case. When mixtures with 50 per cent of heavier component are used, the adsorbed gas has a molecular weight very close to that of the heavier component. This means that a larger amount of the heavier component in the initial mixture will not make much difference in the molecular weight of the adsorbate, whenever the heavier component constitutes more than 50 per cent of the initial mixture.

Influence of Molecular Weight of Initial Gas Mixture: From a study of Fig. 2 (and data recorded for the other systems), it appears that the molecular weight of the adsorbate increases with the difference between the molecular weights of the component gases of the mixture, even if, in both cases, the average molecular weight of the mixture is the same. When the second component is of a much lighter weight, it is to be expected that a much larger proportion of the heavier component is required to

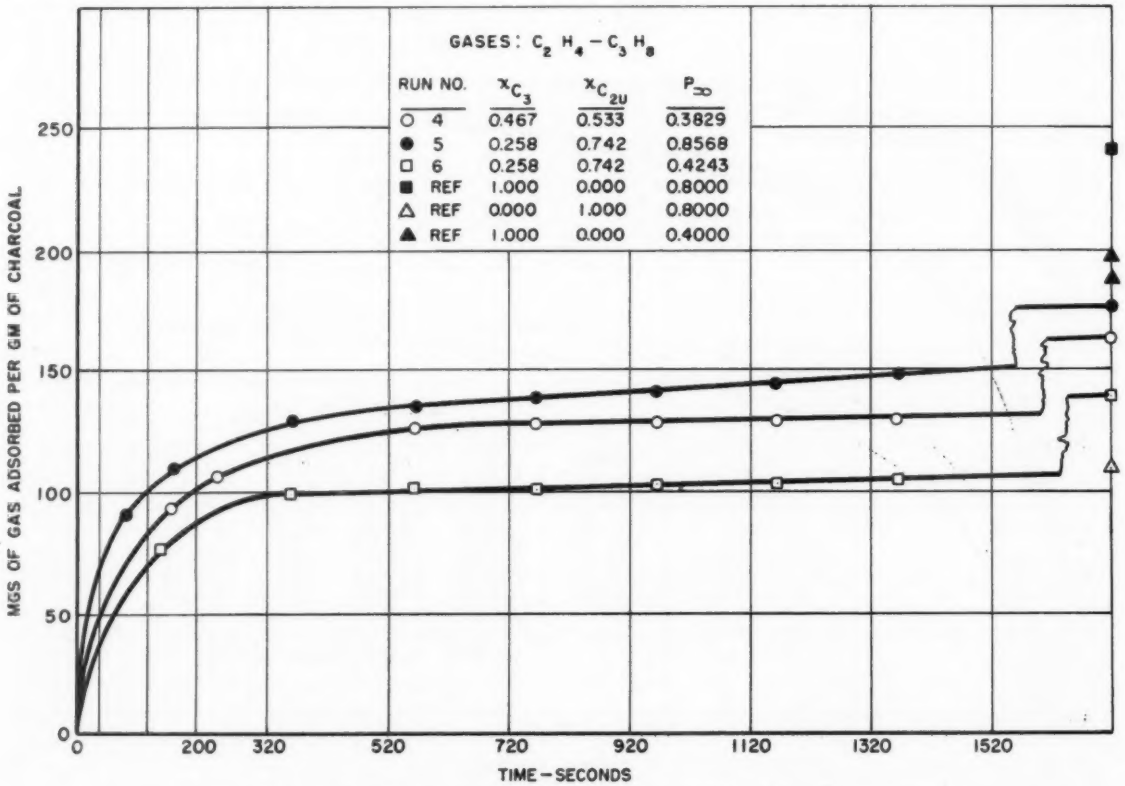

FIG. 3. Rate of adsorption: effect of composition of adsorbate and pressure.

bring up the average molecular weight of the gas mixture; this would justify the findings.

Influence of Pressure: Within the operating pressure range it was hardly possible to have an over-all picture of the influence of pressure on the adsorbed gas. However, Fig. 2 (and other data) permits the comparison of the molecular weight of adsorbed gas when similar mixtures are adsorbed at two different operating pressures.

It was found that, for pressures between 0.3 and 0.8 atmospheres, the influence of the pressure on the adsorbed gas is not always in the same direction.

For the systems ethane-propane, propane-butane, and ethylene-propane, the molecular weight of the adsorbed gas seems to decrease with an increase of pressure; but for the system ethylene-butane, the molecular weight increases with pressure. This variation of the molecular weight with the pressure was small, and was observed for mixtures in which both components were in the same proportion. For larger proportions of the heavier component, the molecular weight of the adsorbed gas tends to reach the same value at both pressures at equilibrium conditions.

These findings are in agreement with those of Lewis,[2] who reports, for higher operating pressures, an increase of the mole fraction of the light component on the adsorbent. The discrepancy in the system ethylene-butane could be an experimental error, as the difference between the two values of the molecular weights obtained at the two different pressures is so very small; however, Holmes[1] whose findings were the same as the writers' for this system, attributed the discrepancy to the fact that Lewis reported data for pressures higher than one atmosphere.

Total Gas Adsorbed: The data shown on Fig. 3 reveal that more gas was adsorbed when operating pressure was higher, as could be expected from the published literature. In all cases, the presence of the second gas seemed to decrease the charcoal adsorption capacity for the first gas; and the total amount of gas adsorbed was always smaller than the weight which one would expect for the heavier component alone. This would indicate that formulas given by Markham and Benton[3] are in qualitative agreement with these experimental data.

Figure 3 presents curves for the system ethylene-propane, prepared by plotting the weight of adsorbed gas per gram of charcoal versus time. To compare these values with those of pure hydrocarbons, data for pure butane and propane, at equilibrium conditions, have been included (Ref. curves). Further observation of these curves, and comparison with those of the other systems, indicates also that longer time is required to reach equilibrium when the run is carried on at a lower pressure.

Finally, to compare with Holmes' data, the molecular weight of adsorbed gas for one of the runs made by Holmes[1] was calculated and included in Fig. 2. It appears that, despite similar final equilibrium values, Holmes' data indicate less time in reaching the equilibrium state. He attributed the shorter time recorded in his research, in comparison to the time reported by Mulvany[4] to the larger amount of charcoal used by the latter. His conclusion seems to be correct, since the present writers used a larger amount of charcoal in their research than did Holmes, and a longer time was required to reach equilibrium.

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ELECTROMAGNETIC FLOWMETER DESIGN AND PERFORMANCE

(Continued from page 23)

flowmeter under proper conditions. Curve D is the uncorrected performance curve obtained from experimental test data and differs from C by the impedance drop correction. A and B coincide, as do C and D, for interelectrode conductances above 2×10^{-4} mho, showing that the correction for sensing-head impedance drop is negligible when interelectrode conductances are higher than 2×10^{-4} mho and the amplifier input impedance is over 470,000 ohms. Exclusive of electrode polarization, theory predicts that all four curves of Fig. 5 should coincide when the interelectrode conductance rises higher than the values mentioned above. The fact that they do not, is directly attributable to the polarization effect.

Conclusions

In conclusion, the following observations can be made. First, a linear calibration curve cannot be considered as the only criterion of flowmeter performance since such a curve does not indicate that theoretical results are even being approached, much less attained. Second, much remains to be accomplished toward acquiring a suitable compromise between noise suppression and good transient response. Third, apparently no fundamental law bars realization of near theoretical flowmeter performance, although much developmental work remains to be done.

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Notes and Comments

MECHANICAL ENGINEERING PROFESSORS RECEIVE NATIONAL RECOGNITION

E. E. Day

H. M. Hendrickson

H. M. Hendrickson, Associate Professor of Mechanical Engineering, who is chairman of the Pacific Northwest Section of the American Society of Refrigerating Engineers, was recently elected for a three-year term as a national director. Professor Hendrickson will edit the forthcoming issue of the *Refrigeration Data Book*, and is a member of the Committee for Cooperation with the National Institute of Refrigeration. At the 50th annual meeting of the Society, held in Philadelphia November 28 to December 1, he was moderator of the forum on air-conditioning.

E. E. Day, Professor of Mechanical Engineering, who was presented with the Pi Tau Sigma Gold Medal Award December 3 at the ASME meeting in New York, gave the main address at the annual Member and Student Luncheon, speaking on the topic "This is My Profession." He is chairman of the ASME Student Relations Committee of Region VII which includes eight western states. Professor Day also attended the meeting of officers of the M.E. Division of the ASEE. He is editor of *Machine Design and Manufacturing Bulletin*, published by the Machine Design Subdivision of the ASEE.

ENGINEERS IN THE NEWS

L. J. Lewis, Professor of Electrical Engineering, presented a paper, "Harmonic Analysis for Nonlinear Characteristics," at the fall general meeting of the AIEE held at Chicago, October 12-15.

W. E. Rogers, Professor of Electrical Engineering, attended the meeting of the New York Academy of Science, October 28-29. His paper on "Construction and Application of Membrane Analogs" was given before the Conference on Instrumentation. While in the East, Professor Rogers inspected the M.I.T. Laboratory for Insulation Research, visited the North Carolina State College to study its Nuclear Reactor Program, and later consulted with the Office of Ordnance Research at Duke University.

J. I. Mueller, Associate Professor, and **E. E. Mueller,** Assistant Professor of Ceramic Engineering, were authors of a paper "Ceramic Vitreology," presented before the White Wares Division at the Pacific Coast Regional Meeting of the American Ceramic Society held at Los Angeles, October 27-29. The former also appeared before the general meeting with "Horizons of Ceramic Engineers in Industry," and before the Heavy Clay Products Division with "Flow Properties of Clay in the Stiff-Mud Extrusion Process," a paper co-authored by **Fremont Burrows,** Orton Fellow. Professor E. E. Mueller and **F. R. Simpson,** Orton Fellow, were on the program of the Enamel Division with "Ground-Coat Enamel for Titanium Metal." Thirteen students accompanied the faculty members to the meeting and were later taken on an inspection trip during which they spent a day and a half at the Gladding-McBean plant at Glendale.

N. J. Marshall, Research Assistant in the Engineering Experiment Station, presented a paper on "Base Exchange Capacity of Clays," before the Engineering Section of the Northwest Scientific Association which met in Missoula, December 29-30.

NORTHWEST ROAD BUILDERS TO MEET

The eighth Northwest Conference on Road Building will be held in Corvallis, Oregon, February 10-11, under sponsorship of Oregon State College. Professor Martin Coopey is general chairman for the conference. As usual the meeting will be attended by county, city, state and federal engineers concerned with roads, and by contractors and industrial representatives who have an interest in highway construction. Members of the Washington State Council for Highway Research are on Professor Coopey's Advisory Committee.

Proceedings of the 1954 Conference, which was held at the University of Washington, are now available and have been sent to all who registered at the 1954 meeting. Others interested in obtaining copies may obtain them by addressing requests to the Department of Civil Engineering, Room 121, More Hall. The price is $1.00.

Power-System Analysis: A Problem in Dynamics

(Continued from page 12)

to reduce the phase error toward zero. Actual motion of the phase control is a function of both the power requirement of the system and the machine properties represented in the computer. The swing curve is obtained by recording directly the measured phase angle, θ_M.

A system corresponding to that in Fig 1 has now been operated at the University of Washington, although the development is by no means complete. The project amply demonstrates the feasibility of the basic idea. Preliminary swing curves have been obtained which check closely with calculations for the system represented. The entire swing curve is obtained in a matter of minutes.

Several aspects of this development are important to analyzer applications. The general principle is not restricted to a particular type of analyzer, although the physical features of analyzers in current use differ widely. The type of instrumentation employed, however, would have to be selected so as to be compatible with other features of the particular analyzer.

Consideration of the computer requirements indicates that a relatively simple unit may be employed, at least if the computer is only to simulate the machine characteristics usually taken into account in present system studies. At present, for purposes of calculation, a very simple representation of the machine is employed, in order to avoid excessive calculation. Customarily, the inertia effects of the machine are included, but any damping is neglected. In the case of the automatic unit, there is not the same compelling reason for simplification. In fact, by only moderate changes in the computer section, the effect of damping can be included, with no increase in time required for making a study. Also, studies usually are based on the round-rotor theory of the alternator, even when the machines are of the salient-pole type. A change in the computer arrangement would permit a more complete representation of machine behavior. Provision could also be made to include the effects of automatic voltage regulators, where such devices need to be considered for the system under study.

The idea of automatic control for an analyzer can be extended to provide a feature which would be particularly beneficial in all studies, besides those involving stability. Before any problem can actually be started, a process of manipulation is required to adjust the analyzer units to the initial conditions of the problem. This is ordinarily quite difficult because of the manner in which initial conditions are specified. For example, a specified amount of the power output may be required at a certain location. However, the load impedance cannot be set because the voltage at the point is initially unknown. Consequently, the best that can be done is to make an estimate of the voltage with the hope that it will turn out to be correct. When the actual voltage is measured, a further adjustment of the impedance is required. When the system is large, and many loads must be modified, the adjustments are not independent, with the result that a lengthy trial and error procedure must be undertaken. By automatic control, using servo-drives for each of the load units, it would be possible to preset each load to the power level desired before turning on the analyzer; the adjustments would then all take place simultaneously and automatically. Equipment required would be similar to a portion of that illustrated in Fig. 1.

The Digital Computer

As an alternate to using the network analyzer for power problems, the digital computer has received some attention.[8] The digital computer may take a variety of forms, beginning with the simple desk calculator. The types appropriate for network studies would include the card-programed computer, such as is used for accounting, and those operating at high speed, utilizing magnetic and electrostatic storage.

Thus far, experience with digital computers in network studies has been quite limited, compared to the 25 years during which network analyzers have been employed. In many respects a direct comparison of the methods is not possible. Nevertheless, some general features of digital computers are significant.

In contrast to the analogue computer, the digital computer has physical features which bear no physical relationship to the system being studied. The relationship is expressed solely through the mathematical equations to be solved and the numerical processes to effect a solution. This is sometimes an advantage, sometimes a disadvantage. Having a physical model with which to work sometimes suggests a procedure to be tried. On the other hand, greater flexibility is achieved when operation is not restricted to a particular pattern. The problem of power flow involving both the hydraulic and electrical systems would seem to be a case in point; probably a digital computer could be equally effective in either realm, whereas the analyzer, being basically an electrical system analogue, has a more restricted application.

The digital computer operates in all mathematical fields, including the solution of simultaneous equations and the solution of differential equations, both linear and nonlinear. There seems to be no question of its capabilities for any of the problems here considered.

The facility and flexibility of digital computer operation is dependent to a great extent on the development of programing procedures. Thus far, applications of computers to power-system analysis have been primarily concerned with electrical load-flow studies. The extent of programing required is not necessarily based on the amount of data introduced into a problem. Thus, basic programing can often be prepared for a whole class of problems; individual problems can then be studied without requiring extensive setup time. A most significant feature of present day high-speed computers is the ability of the machines to adjust and change their own programing as the calculations progress.

When fairly extensive studies are required, the digital computer has advantages, from the standpoint of both speed and accuracy. Analogue procedures involve cumulative errors whose effects are difficult to assess and which become of major concern as problems get larger.

In the planning for future analytical facilities, the operating costs and rental charges for digital computers will need to be contrasted with the extensive capital investments required for a large network analyzer. When the work load of network studies can be combined with other activities in a computing center, the increased volume of work will justify the use of higher-speed digital computers, with their increased flexibility. From the increasing complexity of the problems being encountered, it is evident that the potentialities of computers in this field need to be more thoroughly explored.

Conclusion

The analytical problems reviewed here are but a part of the widespread opportunities for continued research and development in the power field. Many of them will be handled on network analyzers, some of them by improvements as yet not conceived. However, the problems are of such a nature that the digital computer seems destined to become increasingly important.

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Sea-Water Desalting by Refrigeration Approved on Contract

Under a recently signed contract between the University of Washington and the U.S. Department of the Interior, two departments of the College of Engineering will cooperate in a project to study the commercial feasibility of extracting fresh water from sea water by freezing. Dr. R. W. Moulton, Professor of Chemical Engineering, and Professor H. M. Hendrickson, Associate Professor of the Department of Mechanical Engineering, will supervise this combined effort. Dr. Thomas G. Thompson of the Department of Oceanography, whose promising laboratory results over the past several years led to this further step, will be consultant for the project.

According to Dr. Thompson's report, by freezing and subsequent melting of sea water, 75 to 80 per cent of the salt and other minerals can be removed, leaving 30 per cent of the original amount of sea water potable, a figure that can be raised to 50 per cent by freezing the partly desalted waste that first runs off from the controlled "melt."

Research for which the contract provides will be concerned with freezing sea water by means of various commercial types of freezing equipment which are now engaged in making ice from ordinary potable water, and which are available in the area close to the University. The ice made by these various types of plants will be analyzed for salt occlusions by the Department of Chemical Engineering in order to determine the type best suited to putting the process on a commercial basis.

A small pilot plant embodying the promising features, will then be assembled on the campus by the Department of Mechanical Engineering to carry on tests. It will have a capacity of freezing approximately 200 pounds of ice in 24 hours. Sea water will be shipped from Puget Sound in a barge owned by the University. Further tests will then be made with the model to determine the feasibility and economy of the freezing process.

Theoretically, only about one-sixth of the total energy is required to secure a given volume of fresh water by freezing, as compared to distillation, with the further advantage that factors of corrosion are far less serious by freezing methods than by others.

Graduate students, A. Colville, in chemical engineering, who has been working with Dr. Thompson, and Kiem Viet Ly, J. R. Zedro, and H. A. Farman-Farmian, in mechanical engineering, will work on the project under the direction of the departmental supervisors.

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